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FIRE TESTING OF HALF-SCALE ROAD CASK FOR 10 YEAR COOLED IRRADIATED FUEL

Report No 88-127-K

D. Taralis / G. Morandin
Engineer / Technologist
Applied Mechanics Section
Mechanical Research Depertment

ABSTRACT

Fire tests on a half-scale road cask for 10 year cooled irradiated fuel have been caried out by Ontario Hydro Staff using the National Research Council's fire test facilities. This will assist in determining the survivability of the full scale road cask in fire accident scenarios within and beyond regulatory requirements. The cask model was instrumented with 54 thermocouples (T/C's) and one pressure transducer. The flame temperatures required for calculating the fire test duration were obtained from 16 T/C's placed within the fire. Temperature and pressure measurements were made until the cask model had cooled down close to ambient conditions. The results of the measurements indicate that the maximum seal temperatures for the 1/2 hour fire occurred at the drain plug(204 °C). Lid and vent seal temperatures were well below this value. Pressure measurements revealed that there were no gross leaks during or after the fire tests. Post fire examination showed that all seals were in good condition (except the drain cover plate seal which showed signs of deterioration but no leakage). The impact limiter wood burned to a maximum depth of about 40 mm. Fire accident analysis of the half-scale road cask is recommended for verifying the existing analytical tools.

job	file	date	report no.
21-238-461	825.122	May 17, 1988	88-127-K

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FIRE TESTING OF HALF-SCALE ROAD CASK FOR 10 YEAR COOLED IRRADIATED FUEL

D. Taralis / G. Morandin
Engineer / Technologist
Applied Mechanics Section
Mechanical Research Depertment

This report presents the results of two fire tests on a half-scale road cask carried out by Ontario Hydro Staff using the National Research Council's fire test facilities. The purpose was to assist in determining the survivability of the full scale road cask to fire accident conditions within and beyond regulatory requirements. The results of these tests include :

1. Flame temperatures at 16 locations

2. Cask model temperatures at 54 locations

3. Internal cask pressure

4. Post fire examination of seals and impact limiter

The results of the temperature measurements made for the regulatory fire test indicate that the maximum seal temperatures for the 1/2 hour fire occurred at the drain plug (204 °C at the seal). The lid and vent seal temperatures were well below this value. The pressure measurements indicate that there were no gross leaks throughout the fire tests. Post fire examination revealed that the redwood of the impact limiter burned to a depth of about 40 mm. A fire accident analysis of the half-scale road cask should be performed to verify the analytical tools.

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To Mr. H. N. Isaac
Manager
Nuclear Materials
Design & Dev - Gen

FIRE TESTING OF HALF-SCALE ROAD CASK FOR 10 YEAR COOLED IRRADIATED FUEL

1.0 INTRODUCTION

The present study deals with the fire testing of a half-scale road cask in connection with the transportation of 10 year cooled fuel (Reference Case). It involves carrying out one fire test within Atomic Energy Control Board (AECB) requirements (0.5 hour at 800 °C flame temperature on full scale cask) and one fire test beyond AECB requirements (1.0 hour at 800 °C flame temperature on full scale cask). The main objectives of this study are as follows:

i) To determine the temperature range occuring at the seal locations

ii) To obtain fire and model temperatures for verifying analytical modelling.

As a separate project a video was made of these tests for public relations. To meet the above requirements it was necessary to find a suitable fire test facility. On the basis of the needs of this study it was determined that the Institute for Fire Research in Construction of the National Research Council (NRC) of Canada was suitable for conducting the required tests within the tight schedule.

This report describes briefly the NRC fire test facility, the test apparatus, the intrumentation used for making temperature and pressure measurements and the data acquisition system. In addition this report presents and discusses the results of both fire tests as well as the results of the post fire examination and states the major conclusions and recommendations of this study.

2.0 FIRE TEST FACILITY

In determining where to conduct the fire tests two test facilities were considered. For technical reasons and time schedule the NRC Fire Hall was found to meet our strict requirements and therefore the tests were conducted there. The facility is situated in the country approximately 60 km west of Ottawa. The facility (see also Reference /1/) is a large hall with approximate dimensions of 30 m x 55 m in cross section and 12 m in height. A photograph of the building is shown in Figure 1 . The building has two large doors; one on the South and one on the North. Around the walls of the hall near the ceiling there are baffles that can be opened to allow excess smoke to escape from the building.

3.0 TEST APPARATUS

This section describes the experimental apparatus that has been employed in conducting the fire tests at the NRC fire test facility.

3.1 Half-Scale Road Cask

Figure 2 shows a schematic diagram of the half-scale road cask. It is made of stainless steel (304L) and consists of the main body and the lid bolted together using two Viton O-rings for sealing the cavity. The cask is equipped with a vent on the lid and a drain near the bottom at the middle of one of the sides of the cask. The vent and the drain have similar sealing designs. The cask model has been designed according to the ASME pressure vessel code, section VIII, Division 1. The half-scale road cask had previously been drop-tested. This damaged the trunnion, the drain cover plate and one of the bottom corners of the cask model.

3.2 Impact Limiter

Figure 3 shows schematically the impact limiter that was used over the lid during the fire tests. One of its corners had been damaged during the drop tests that were carried out to simulate the hypothetical accident conditions. It is made of redwood encased in stainless steel sheet metal. The purpose of the impact limiter is to absorb enough force of impact so as to protect the lid during impact and also to act as a thermal insulator for protecting the lid seals under fire accident conditions.

3.3 Cask Model Support

The cask support used for supporting the cask model within the fire is shown in Figure 4 (see also Reference /1/). As can be seen from this figure it was made of four vertical steel posts of rectangular cross section and 8 horizontal members of the same size . To increase the strength of the support members the hollow parts were filled with concrete. In addition to reduce the fire heat input to the support frame, all of its members were wrapped with fiber frax blanket.

3.4 Fire Pan and Fuel Supply

A schematic diagram of the the fire pan is shown in Figure 5 (see also Reference /1/). The geometry of the pan is cylindrical with a diameter of 3 m and approximately 0.3 m high. The pan was made of 6.35 mm carbon steel plate. The pan was filled with water to approximately 200 mm with a 20 mm kerosene fuel layer on the top. To break up wave formation while feeding fuel to the pan during the tests and to reduce the effects of surface boiling a number of concrete blocks were placed within the pan. Figure 6 shows the fuel supply system which consists of three elevated barrels interconnected to the fuel supply line. As this figure reveals the fuel was fed to the pan by gravity.

3.5 Thermocouple Supports

In making temperature measurements within the fire four posts were built from carbon steel pipes. Each pipe was vertically supported by means of a base plate which was sufficiently heavy for providing good stability. The posts were drilled with numerous holes for supporting the thermocouple extension arms at the desired elevations. To prevent sagging of the arms due to high temperature they were further supported to the top of each post using high temperature resistant wire. Figure 7 shows in detail one of the flame thermocouple supports.

4.0 INSTRUMENTATION

4.1 Thermocouples

In total 71 Thermocouples were used to make the temperature measurements at the desired locations. In determining the thermocouple specifications the following parameters were considered:

i) Diameter and material of the outside sheath

ii) Accuracy of the temperature measurements (2 % to 8 % error) in the range of 0 to 1100 °C.

iii) Sealing the cavity for pressure measurements.

On the basis of the above considerations ungrounded 1/16 stainless steel sheath type K (Chromel-Alumel) thermocouples were selected for this application. Each thermocouple was approximately 20 m long and consisted of 8 m stainless steel sheath section (for fire environment) with the remaining 12 m section made of teflon sheath (for outside the fire environment). The effect of radiation losses from the flame thermocouple junctions were investigated in the laboratory using three concentric, open-ended, circular cylindrical tubes fabricated from 0.08 mm stainless steel foil. The temperature measurements with and without the radiation shield showed no significant difference. From this it was concluded that the radiation losses from the T/C's junctions could be neglected. The location of the flame and cask model thermocouples are shown in Figures 8 and 9 and the numbering scheme used in Figures 10 and 11.

4.2 Pressure Transducer

The cavity pressure due to the temperature rise of the air within the cavity was measured using an electronic pressure transducer which covered the range from 0 to 750 (kPa)g with less than 0.5% error. A DC power supply of 10 Volts was used to power the transducer. The output voltage from the transducer was automatically converted to pressure units by the data acquisition system which is briefly described in the following section.

5.0 DATA ACQUISITION SYSTEM

Temperature and pressure measurements as a function of time were made using the AUTO DATA 10 data acquisition system (see Figure 12) . This system has the capability of accepting over 100 inputs and allows each channel to be programmed to a different type of thermocouple (7 types available including type K). The temperatures and pressure at the instrumented locations were taken every 15 seconds during the fire tests and less frequently after the fire (varying from every 30 seconds to every 10 minutes) for a total period of about 20 hours. As measurements were made they were recorded on the following devices:

i) Data Cartridge Recorder

ii) Compaq Portable II Computer

The AUTO DATA 10 was programmed to send the data to the above devices via its two RS-232 output serial ports. The system was also programmed to perform a series of calculations required during the fire tests. Specifically the following calculations were performed.

a) Time average of the 16 flame temperatures

b) Required test duration based on scaling laws /2/

c) Elapsed time from the start of the test

d) Remaining time before the fire goes out

The above quantities were computed from the equations given below:

$$\bar{T}_F = \left\{ \frac{T_1 + T_2 + T_3 + \cdots + T_n}{n} \right\} \quad (1)$$

$$t_D = C \left\{ \frac{1278}{\bar{T}_F} \right\}^4 \quad (2)$$

$$t_E = t_C - t_S \quad (3)$$

$$t_R = t_D - t_E \quad (4)$$

Where :

$\bar{T}_F$ = time average of flame temperature, °C in eq.(1) or °K in eq.(2)

T_1 , T_2 ,...., T_n = average flame temperatures from 16 flame T/C's, °C at n time intervals

n = number of equal time intervals

C = 450 s for test within AECB requirements
= 900 s for test beyond AECB requirements

t_D = test duration, s

t_E = elapsed time, s

t_C = current time, s

t_S = start time, s

t_R = remaining time, s

6.0 FIRE TESTS AND RESULTS

This section briefly describes the fire tests conducted at the NRC fire test facility and presents the results of the temperature and pressure measurements.

6.1 Trial Test

Before conducting the fire tests within and beyond AECB requirements a trial test was carried out to provide the following information:

a) cask model support height to ensure fully engulfing fire

b) positioning of the 16 flame T/C's within the fire

c) check of the AUTO DATA 10 calculations

d) time for fire to go out after fuel supply has been turned off

e) positioning of the video equipment

In the trial test the cask model was approximately represented by a set of concrete blocks as shown in Figure 13. The duration of this test was approximately 7.5 minutes which was adequate to obtain all the necessary information required for the subsequent

two tests. The flame temperatures obtained from the 16 T/C's during the trial run are shown in Figure 14 . The time it took for the fire to go out after the fuel valve was closed was about 3.5 minutes. A review of the video footage taken for the trial run revealed that certain changes to the set up were required to obtain a more engulfing fire. The cask model support frame was therefore shortened by 150 mm and relocated inside the pan . Also some adjustment of the 16 flame T/C's locations was made so that the flame temperature data would be more representative of the fire environment seen by the cask model.

6.2 Fire Test within AECB Requirements

First the 1/2 scale cask model with the impact limiter over the lid was placed on the support and preheated (see Figure 15) to an even temperature of approximately 60 °C for simulating the initial conditions of the actual road cask with insolation (solar heating) and fuel. Subsequently the four posts with the extension rods carrying the 16 flame T/C's were placed around the cask model. Figure 16 shows a photograph of the cask model just before the AECB fire test commenced.

When the video equipment and the data acquisition system were ready the signal for starting the fire was given. Figure 17 shows an NRC man in a fire suit using a propane torch to ignite the kerosene fuel which had a thin layer of gasoline on the top for facilitating the ignition process. The development of the fire is shown in Figures 18 and 19 . A fully engulfing fire was established approximately 35 seconds after ignition. As can be seen from Figure 20 the flame fully engulfed the test model.

Figure 21 shows the instantaneous flame temperatures for each of the four posts (4 curves/post) obtained from the 16 flame T/C's. The same results are shown in Figure 22 for four different elevations (4 curves/elevation) . Figure 23 shows the calculated instantaneous flame temperatures of the four posts. Figure 24 shows the average instantaneous and the time average of the flame temperature based on the 16 flame T/C readings. The test lasted approximately 11 minutes (corresponds to 1/2 hour fire on full scale cask). To meet scaling requirements this time period was continuously recalculated throughout the test at 15 second intervals. The time average of the flame temperature was used in equation (2) as it was relatively steady (880 °C during the test period).

The temperatures measurements made on the cask model are presented in Figures 25 through 29. The maximum cask wall temperature at the end of the fire was 645 °C and occurred at one of the middle corners of the cask model (see Figure 25). The outside surface of the impact limiter reached temperatures

(see Figure 26) which were very close to the flame temperatures (800 to 1000 °C) as expected since the stainless steel sheet encasing the redwood is very thin (3 mm). The outer lid temperatures are shown in Figure 27. As can be seen from this figure lid temperatures remained below 150 °C throughout the test.

The maximum seal temperatures occurred at the drain. The temperature of the plug reaches a maximum value of 204 °C at t= 2000 s. This compares well with the calculated value of 194 °C /3/. The cover plate seal temperature was of course higher (354 °C) since this seal is close to the outside of the cask wall. Lower temperatures for the cover plate seal could be accomplished by placing it further into the cask wall. Figure 29 shows the inner wall temperatures and the air temperature at the centre of the cavity. The maximum inner wall temperature attained was 208 °C while the cavity air reached a value of 160 °C.

Prior to the fire test the cask model was pressurized to 186 (kpa)g for detecting any major leaks. Figure 30 shows the pressure measurements during the entire test. The pressure reached a maximum value of 255 (kpa)g sometime after the fire and it declined thereafter. The smooth pressure curve indicates that no gross leaks occured during the test.

The major results of this test are summarized for convenience in Table 1 .

6.3 Fire Test Beyond AECB Requirements

Following the first fire test the cask model was allowed to cool down to ambient conditions . Before starting the second test the cask surface was cleaned of soot deposits and the T/C extension arms were supported again using high temperature wire to avoid sagging during the fire. The procedure for carrying out the extended fire test was identical to the previous test. However this test was of much longer duration, being equivalent to 1 hour at full scale.

As before temperature and pressure measurements were made over a period of about 20 hours. The flame temperatures obtained at the four posts are shown in Figure 31. As can be seen from this figure the fluctuations of the flame temperature were much larger in comparison to the first test. These fluctuations become more pronounced with time which is probably the result of insufficient air in the burn hall. The same results are shown in Figure 32 but for four elevations. Each elevation covers 4 T/C's around the circumference of the pan. Figure 33 shows the average instantaneous flame temperatures of the four posts based

on the 16 flame T/C's readings. The test duration based on the time average of the flame temperature shown in Figure 34 was approximately 26 minutes which is equivalent to 1 hour in full scale. As in the first test the use of the time average of the flame temperature (approximately 840 °C during the test period) leads to more stable test duration because the flame temperature fluctuations have been dampened by the averaging process.

Figures 35 to 40 show the remaining results of the second test. Basically these results are similar to the results of the previous test except that higher temperatures and pressure were attained as a result of the longer test duration. The maximum temperatures and pressure attained during this test at locations of interest are summarized in Table 2.

Figure 41 shows the cask model at the end of the test beyond the AECB requirements. The next section presents and discusses the results of the post fire examination performed at the Ontario Hydro Research Laboratory.

7.0 POST FIRE EXAMINATION

In the post fire examination the following items were visually examined:

i) Outer surface of cask and impact limiter

ii) Seals of lid,vent and drain

iii) Redwood of impact limiter

A close examination of the cask outer surface revealed that a black layer of soot covered the entire surface of the cask body. However the outer surface of the impact limiter remained practically free from soot deposits. As can be recalled from Figures 26 and 36 the temperatures of the sheath encasing the redwood were very high and close to the flame temperatures. This tends to indicate that soot particles do not readily stick to very hot surfaces but they are carried up with the hot gases of combustion.

To examine the lid seals, the cask model was opened (see Figure 42) by first removing the impact limiter and then the lid bolts. The lid seals as can be seen in Figure 43 are in good condition. That is, they retained their original shape, colour and elasticity. Also the condition of the vent and drain seals appears good as Figures 44 and 45 indicate except the cover plate seal of the drain which was partially deformed and stuck to the cover plate due to the high temperature attained during

the extended fire test. It should be mentioned that the lid and vent seals went through both fire tests but the drain seals were changed after the first test.

To find out what happened to the redwood inside the stainless steel casing the impact limiter was cut diagonally as shown in Figure 46. As can be seen from a close up picture (Figure 47) the redwood burned near the sheath to a depth which varied from 25 to 40 mm. The inner part of the wood retained its original condition and therefore the impact limiter should still continue to behave close to an ideal thermal insulator.

8.0 CONCLUSIONS

The main results of this experimental investigation are as follows:

a) The time average of the flame temperature during both fire tests (880 °C for the first test and 840 °C for the second test) was, according to scaling laws /2/, below the required temperature of 1005 °C. Because of this inadequate flame temperature the regulatory fire test lasted approximately 11 minutes instead of 7.5 minutes which corresponds to 1/2 hour for the full scale cask. Also the extended fire test lasted about 26 minutes instead of 15 minutes which corresponds to 1 hour fire for the full scale cask.

b) Flame temperatures for the 1/2 hour or regulation length test fluctuated around a mean value of 880 °C (see Figure 23) with ± 100 °C fluctuations. However, for the 1 hour or beyond regulation length test the flame temperatures fluctuated more severely about a mean value of 840 °C (see Figure 33) with fluctuations of ± 300 °C. Probably insufficient air in the hall was the major reason for these fluctuations.

c) The maximum temperature of the cask outer surface was approximately 645 °C for the test within AECB requirements and 670 °C for the test beyond regulations. These maximum temperatures were attained at the end of the fire .

d) Outside temperatures of the impact limiter reached values which were very close to the flame temperatures (800 to 1000 °C). This is to be expected since the stainless steel sheath encasing the redwood is very thin.

e) The maximum seal temperatures occurred at the drain. For the test within regulations the plug seal temperature was approximately 204 °C (this compares well with the calculated

value of 194 °C /3/). The cover plate seal temperature was not calculated but was measured as 354 °C. For the extended fire test the plug and cover plate seal temperatures were 308 °C and 413 °C respectively. This exceeded the maximum allowable operating seal temperature of 260 °C (see (g) below).

f) Due to the thermal insulating effects of the impact limiter the lid seals and vent seals experienced much lower temperatures than the drain seals. For the AECB test the maximum lid seal temperature was about 114 °C which also compares favourably with the calculated value of 111 °C /3/. The vent seal temperatures were lower. For the extended duration fire test the maximum lid seal temperature attained was 180 °C.

g) The seals performed well throughout both fire tests since there was a pressure rise in the cask cavity (see Figures 30 and 40). All the seals were examined and found to be in good condition except the drain cover plate seal which was partially melted and stuck to the seal grove.

h) Also post fire examination of the cask model and impact limiter was performed visually. The cask model was covered with black soot due to relatively low cask temperatures. This however was not the case with the impact limiter which was the result of the sheath being heated to high temperatures (800 to 1000 °C). By cutting the impact limiter it was observed that the redwood charred to a depth of about 20 to 40 mm.

i) The effects of soot deposits on the outside surface of the cask could be beneficial in terms of reducing the heat conducted into the cask wall particularly for fires of longer duration, and should therefore be investigated.

9.0 RECOMMENDATION

It is recommended that an analysis of the half-scale cask test set-up be performed with the objective to validate the analytical models by comparing the predicted and measured results.

ACKNOWLEDGEMENTS

The authors wish to express their gratitute to Messrs J.F. Tanaka , D.J. Ribbans and P.R. Mitchell of the Nuclear Materials Management Department for providing us with this challenging task and for their continuous input throughout the progress of this work . Special thanks go to the NRC staff at the Fire Research Centre , particularly to Messrs I. Oleszkiewicz and G. Crampton for their assistance and excellent cooperation in conducting the tests.

Approved by:

G.J. Clarke
Manager
Mechanical Research Dept

DT:dt

Submitted by:

D. Taralis

D. Taralis
Engineer
Applied Mechanics Section

G. Morandin

G. Morandin
Technologist
Applied Mechanics Section

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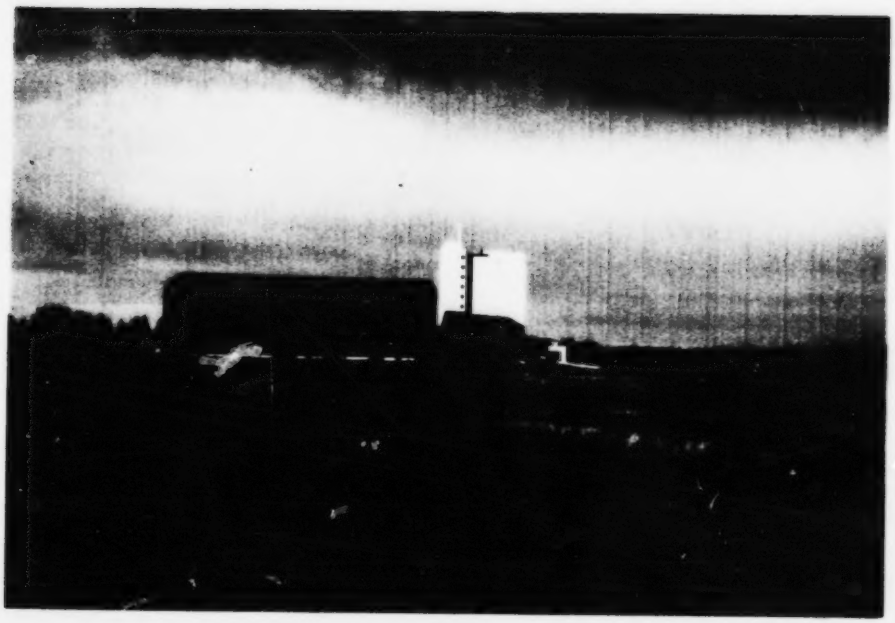
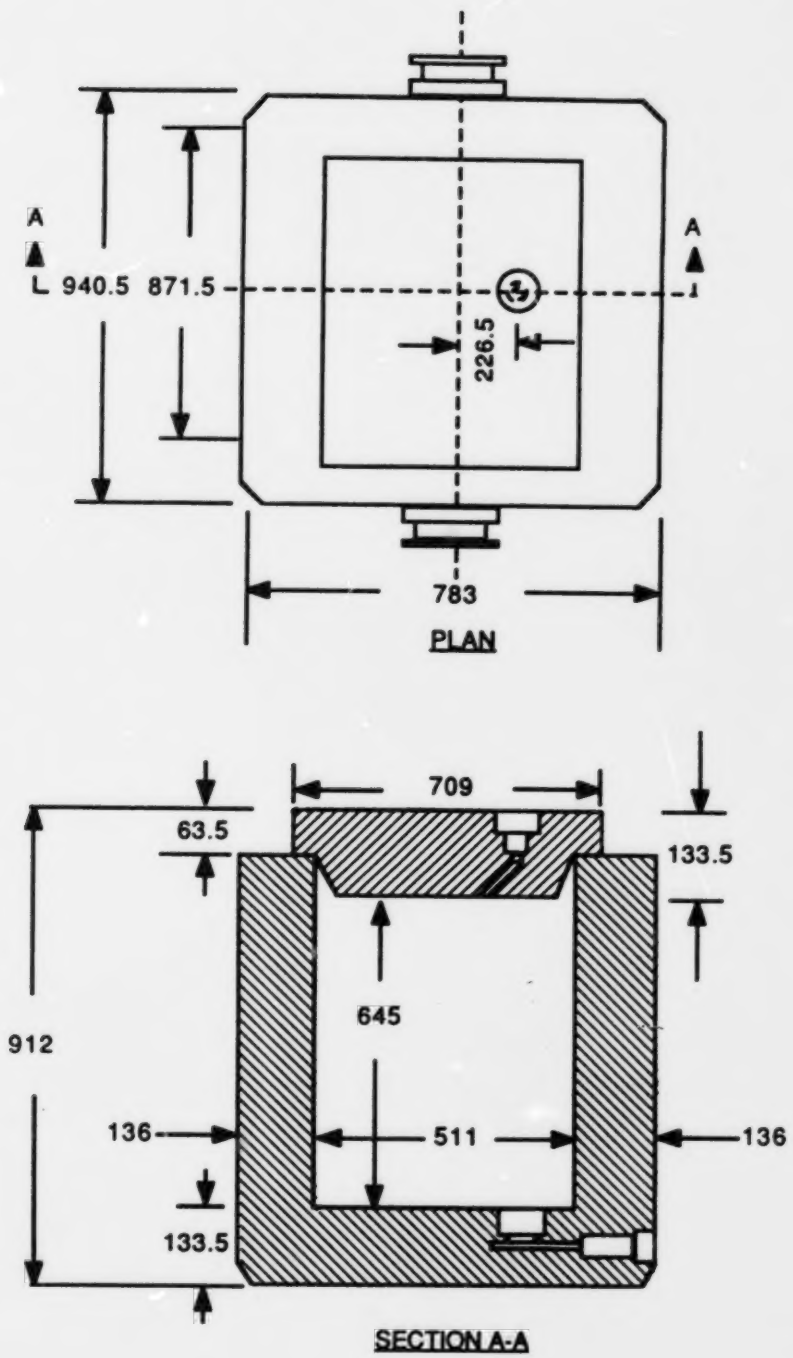


FIGURE 1
NRC FIRE TEST FACILITY

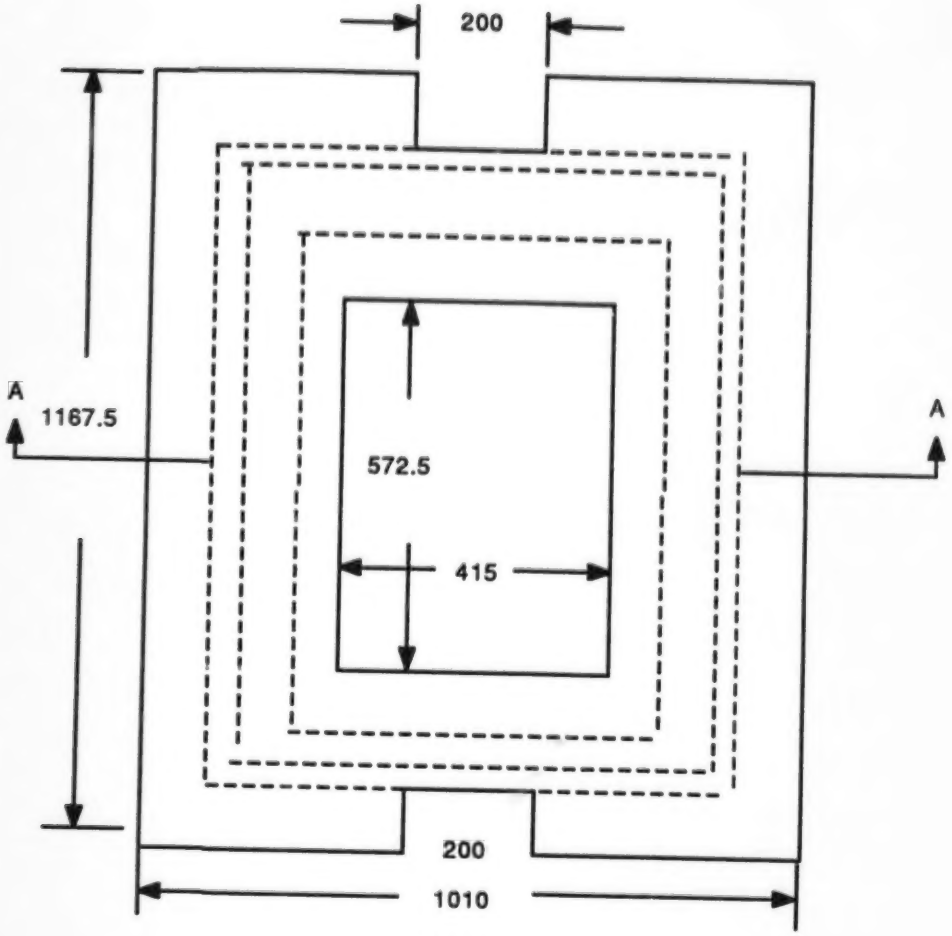


All Dimensions in mm

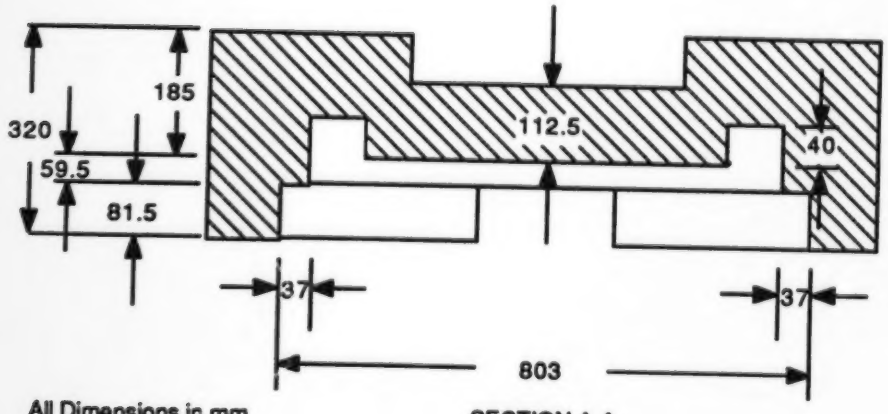
FIGURE 2

HALF-SCALE ROAD CASK

176563-RD
CHUCK DISC2
88-127



PLAN



All Dimensions in mm

SECTION A-A

FIGURE 3

IMPACT LIMITER

88-127
176564-RD
CHUCK DISC2

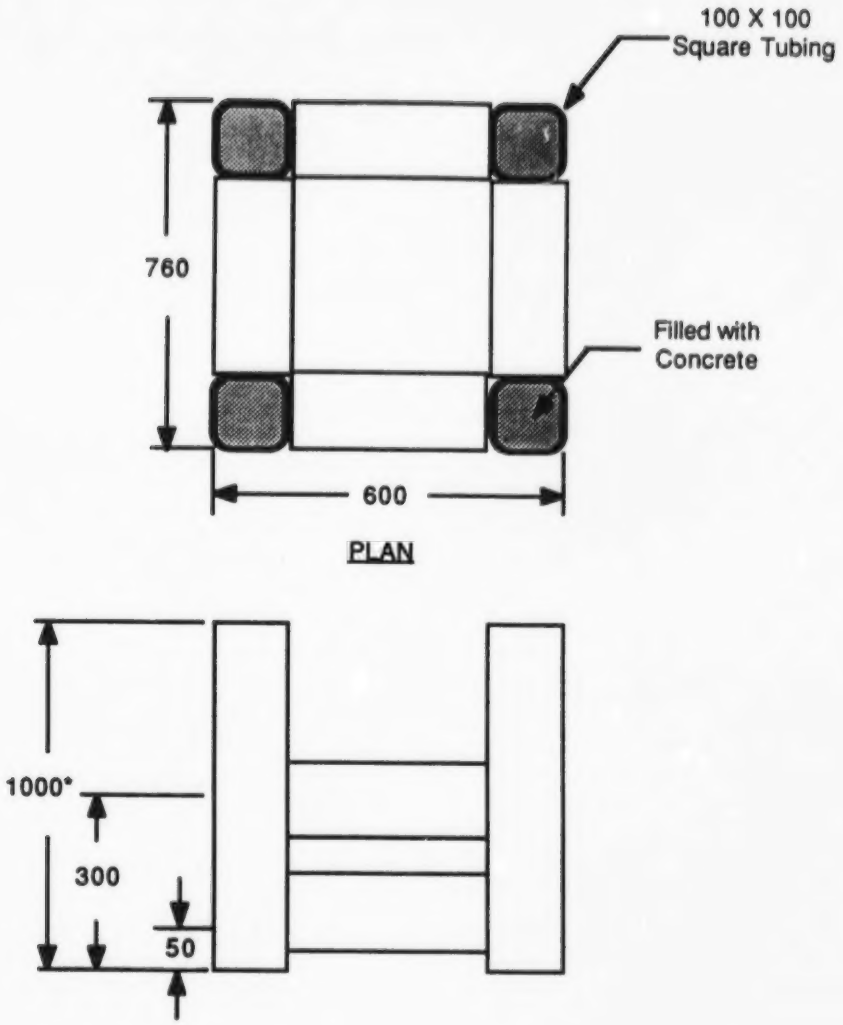


FIGURE 4

CASK MODEL SUPPORT

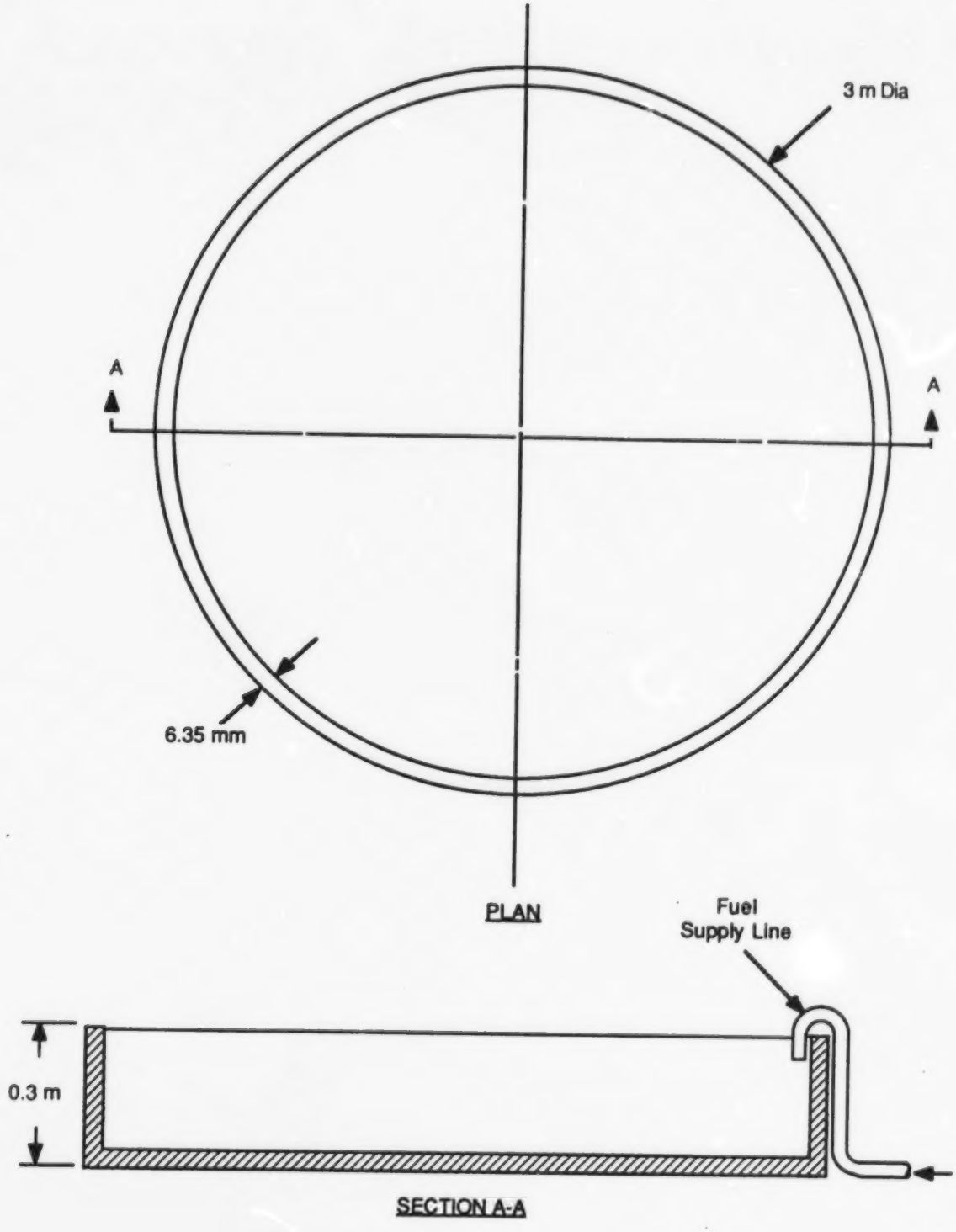


FIGURE 5

FIRE PAN

88-127
176565-RD
CHUCK DISC2

FIGURE 6
FUEL SUPPLY SYSTEM

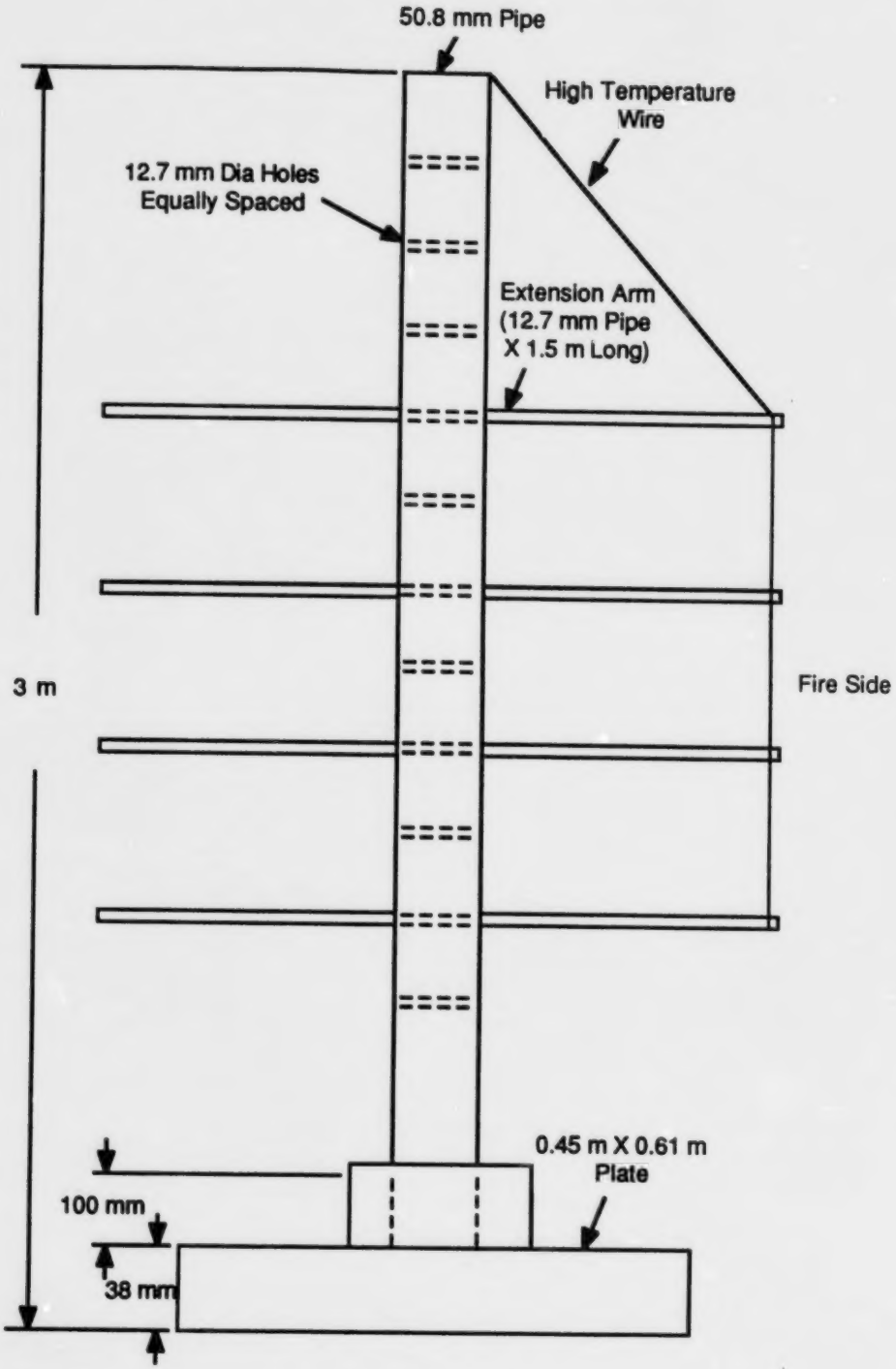


FIGURE 7

FLAME T/C'S SUPPORT

88-127
176566-RD
CHUCK DISC2

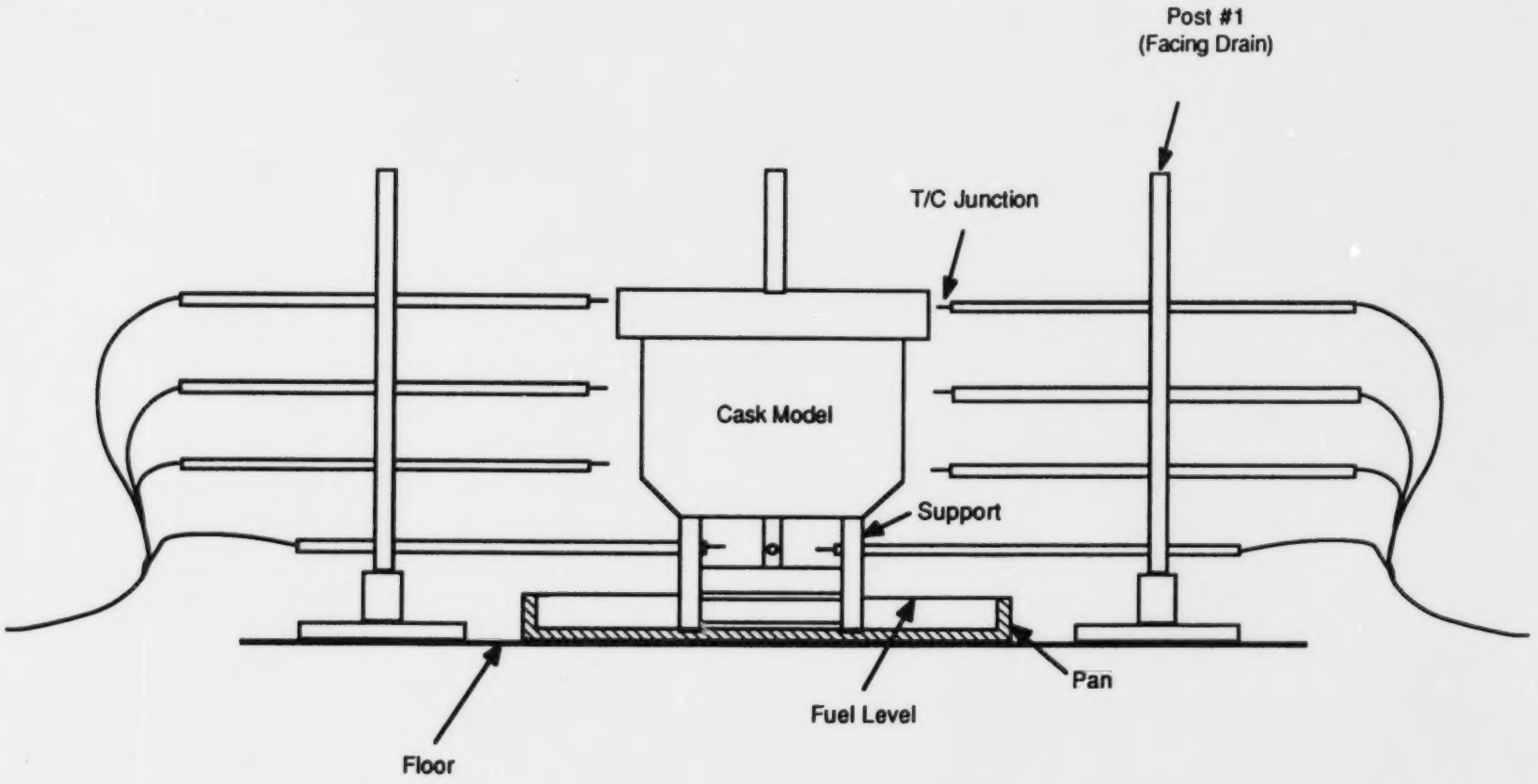


FIGURE 8

LOCATION OF 16 FLAME THERMOCOUPLES

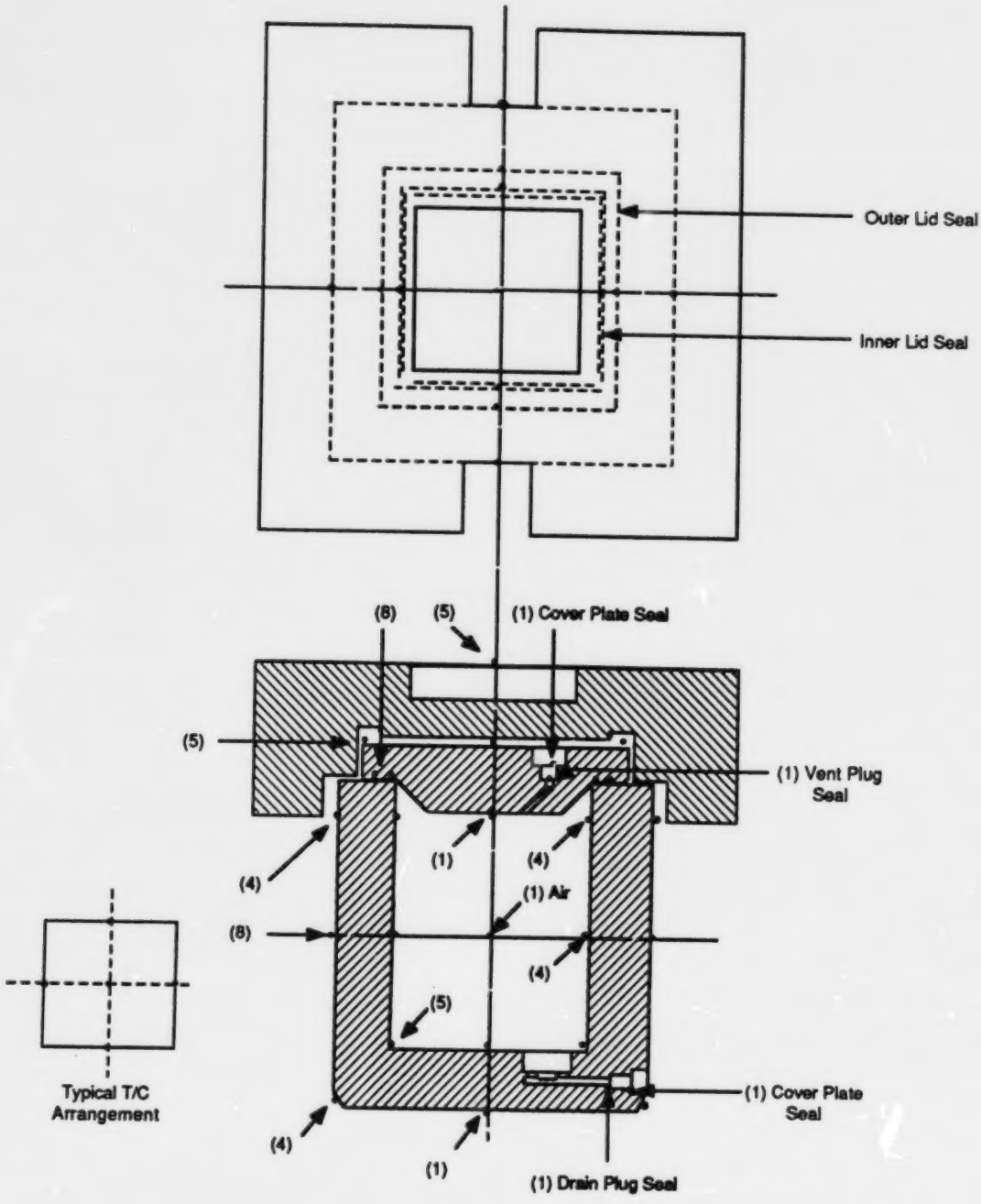


FIGURE 9

LOCATION OF 54 CASK MODEL THERMOCOUPLES

88-127
176568-RD
CHUCK DISC2

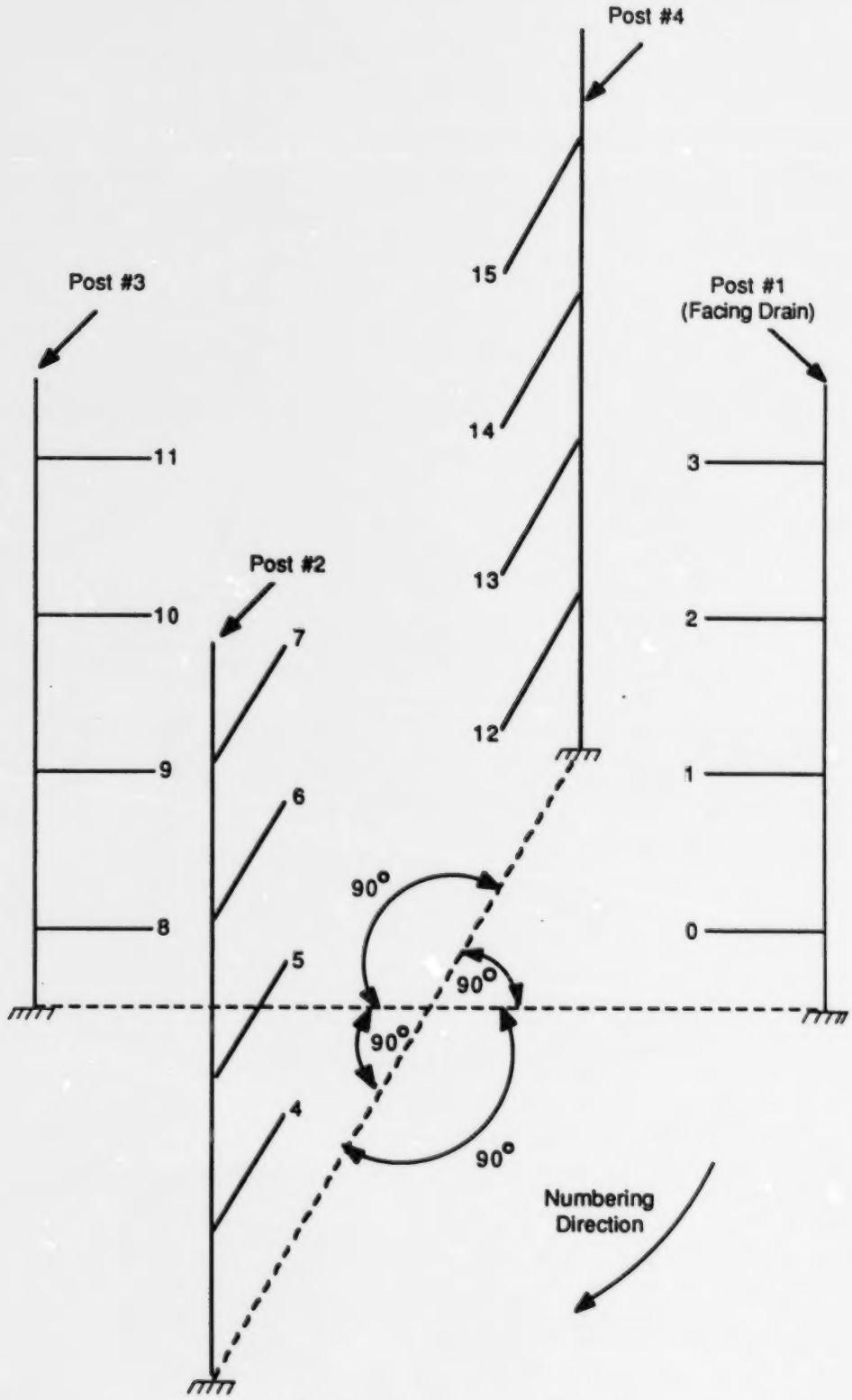


FIGURE 10

NUMBERING SCHEME OF 16 FLAME THERMOCOUPLES

88-127
176569-RD
CHUCK DISC2

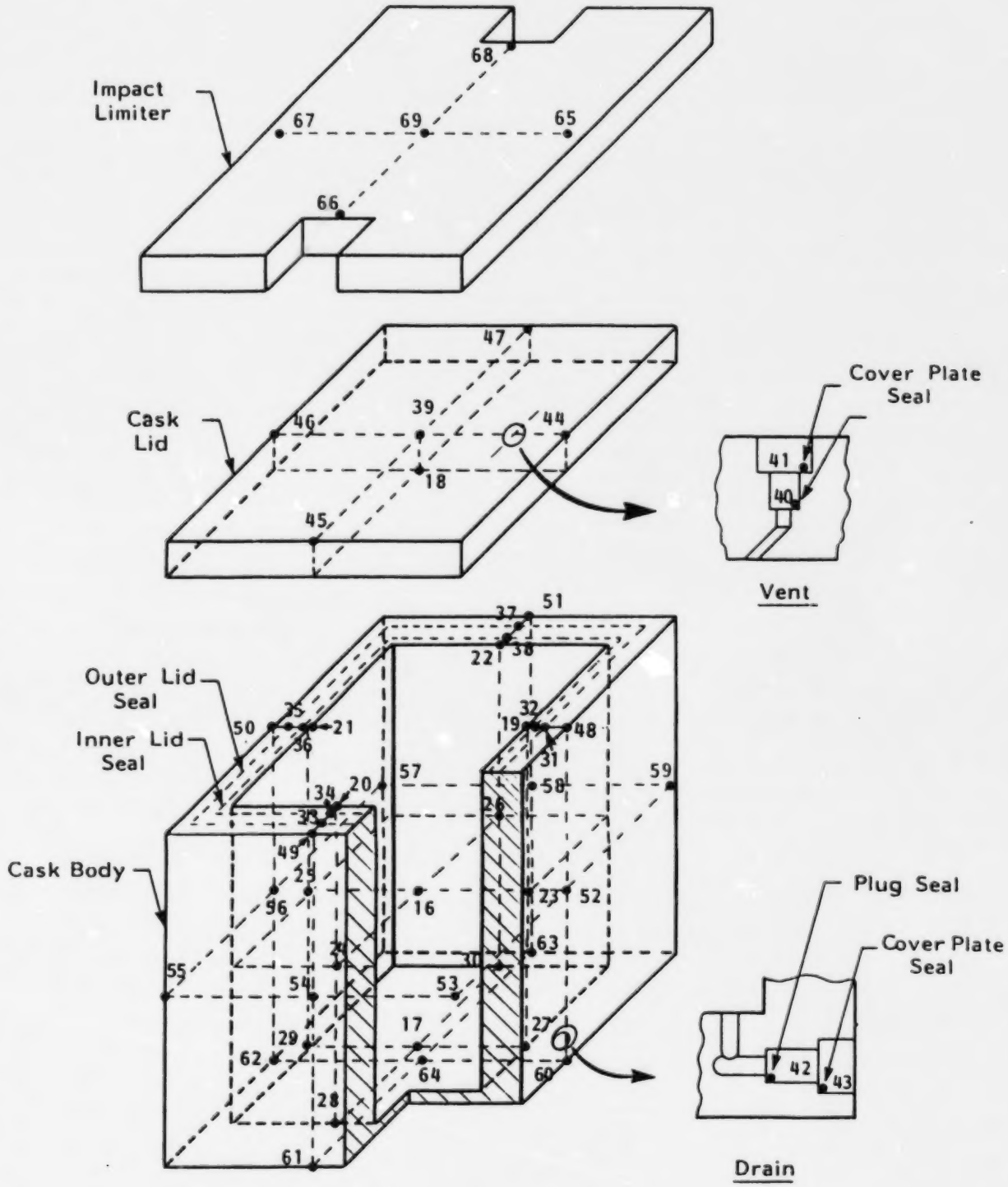


FIGURE 11

NUMBERING SCHEME OF 54 CASK MODEL THERMOCOUPLES

88-127
176571 RD

FIGURE 12

CONTROL ROOM AND DATA ACQUISITION SYSTEM

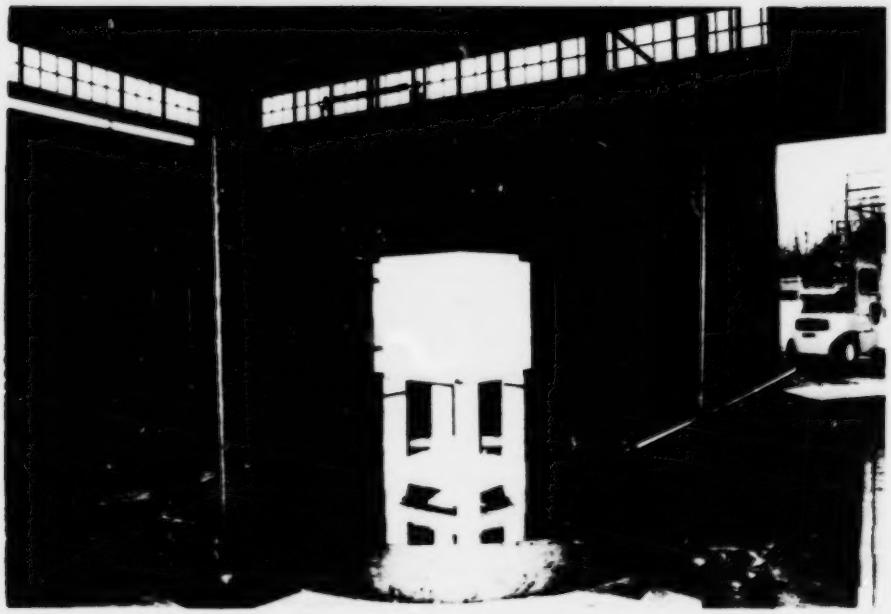


FIGURE 13

EXPERIMENTAL SET UP FOR TRIAL TEST
(CASK REPRESENTED BY CONCRETE BLOCKS)

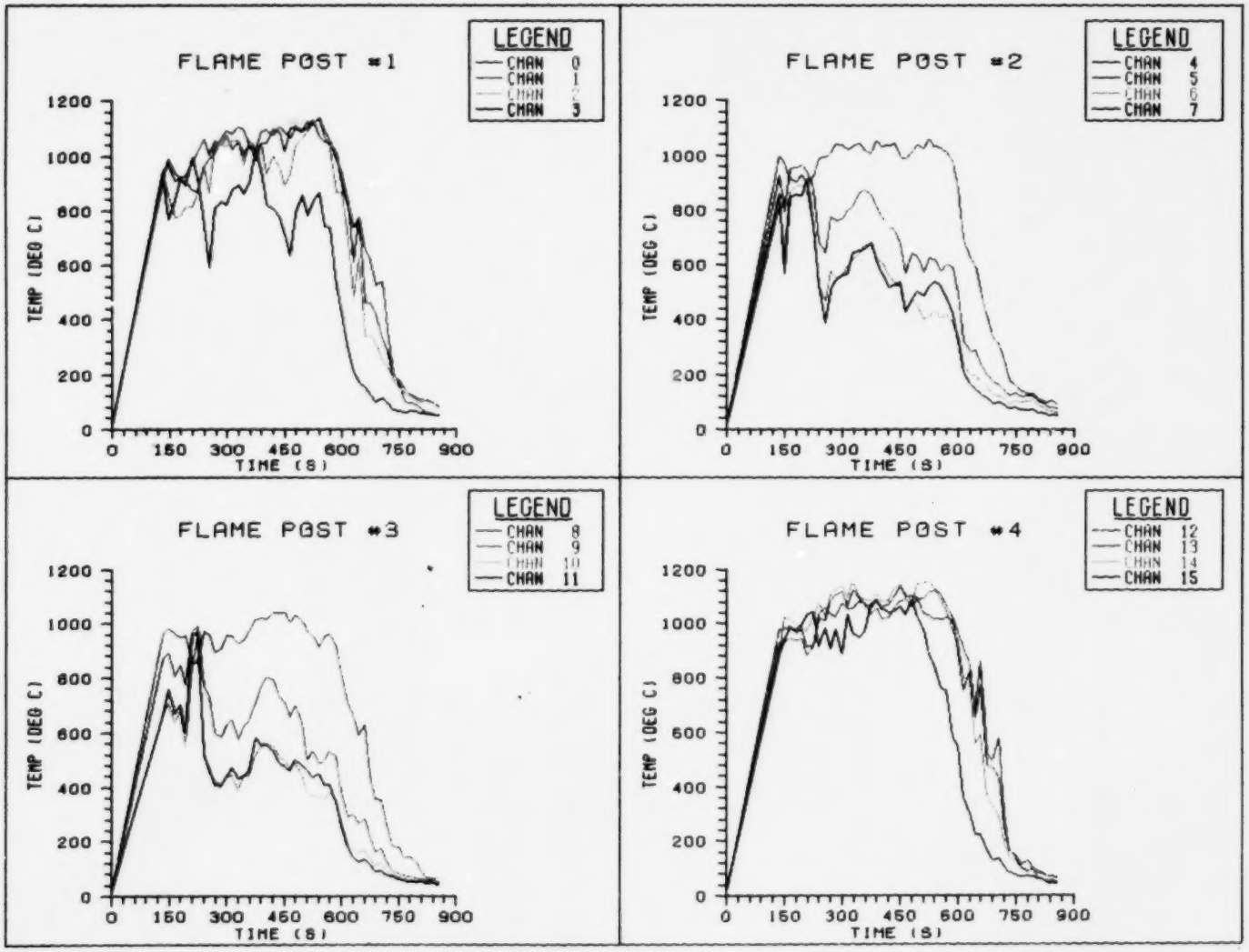


FIGURE 14

FLAME TEMPERATURE AT FOUR POSTS
(TRIAL TEST)

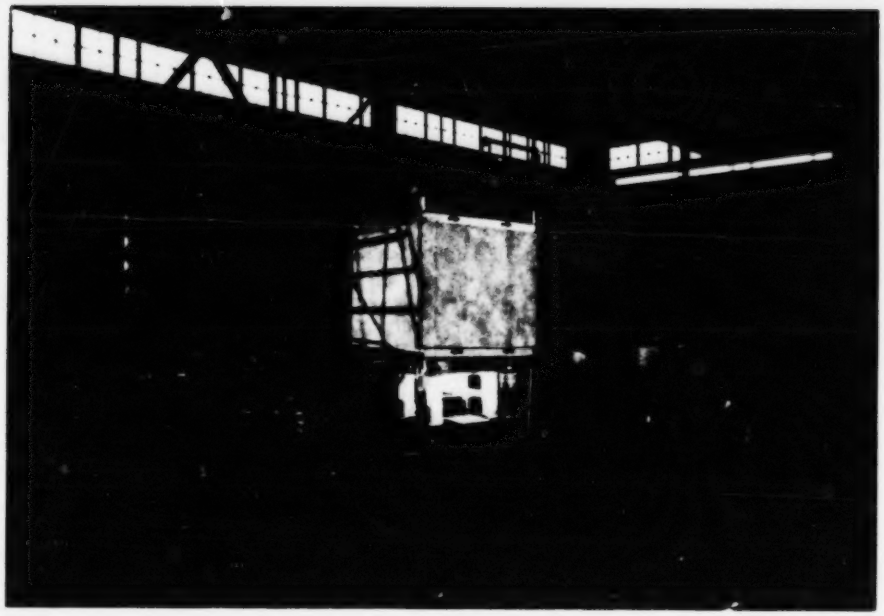


FIGURE 15
PREHEATING OF CASK MODEL

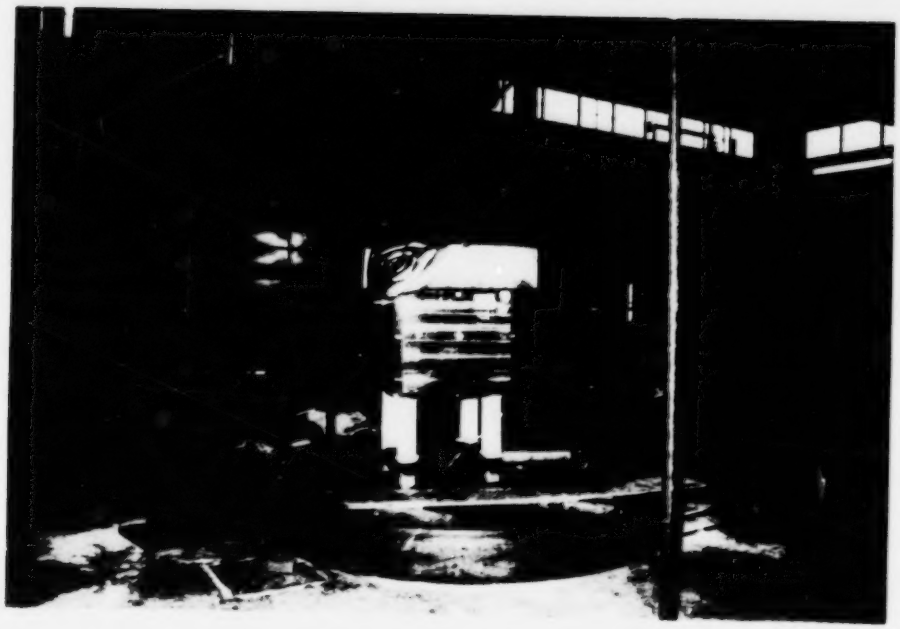


FIGURE 16
EXPERIMENTAL SET UP FOR TEST WITHIN AECB REQUIREMENTS

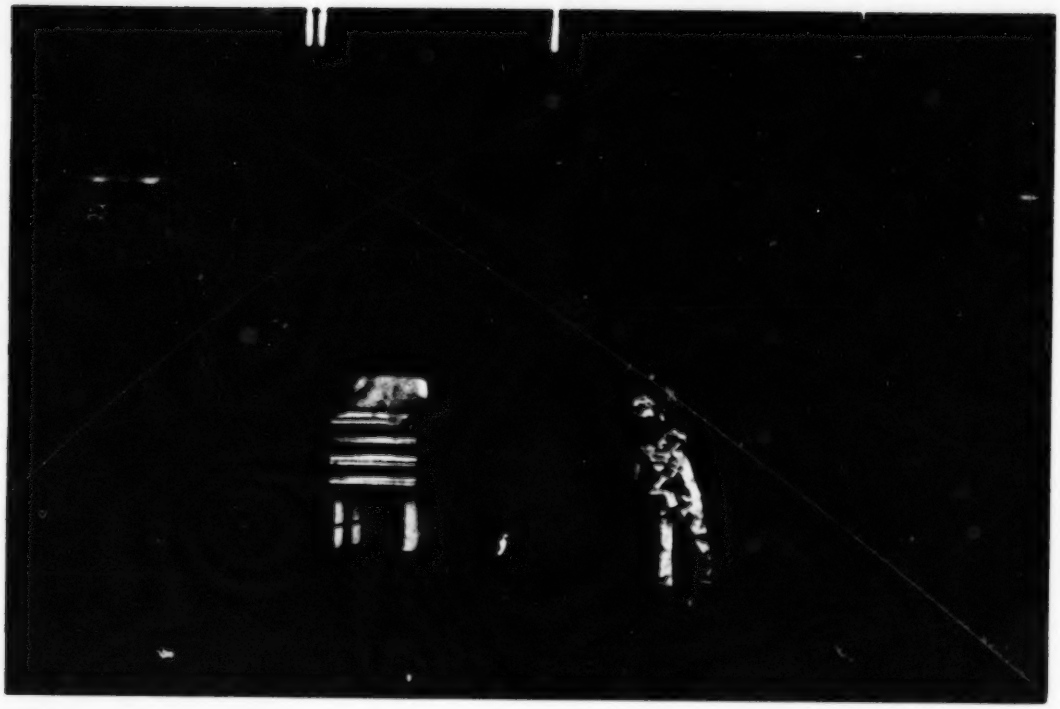


FIGURE 17
NRC MAN IGNITING KEROSENE FUEL

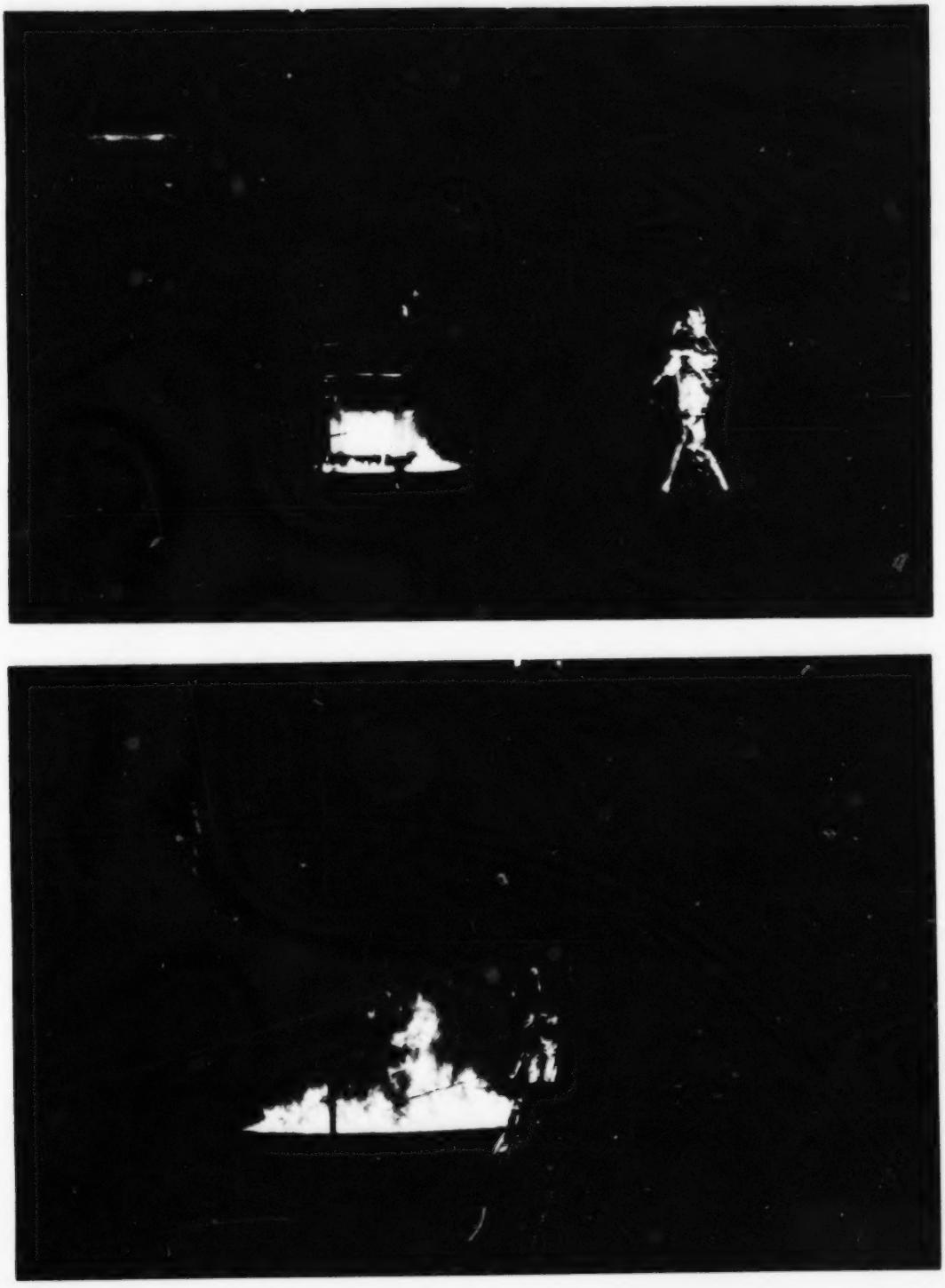


FIGURE 18
INITIAL STAGES OF FIRE DEVELOPMENT

FIGURE 19

NRC MAN LOOKING INTO THE FIRE
WITH A SENSE OF ACCOMPLISHEMENT AS THE
FIRE CONTINUES TO DEVELOP

88-127
176526-RD

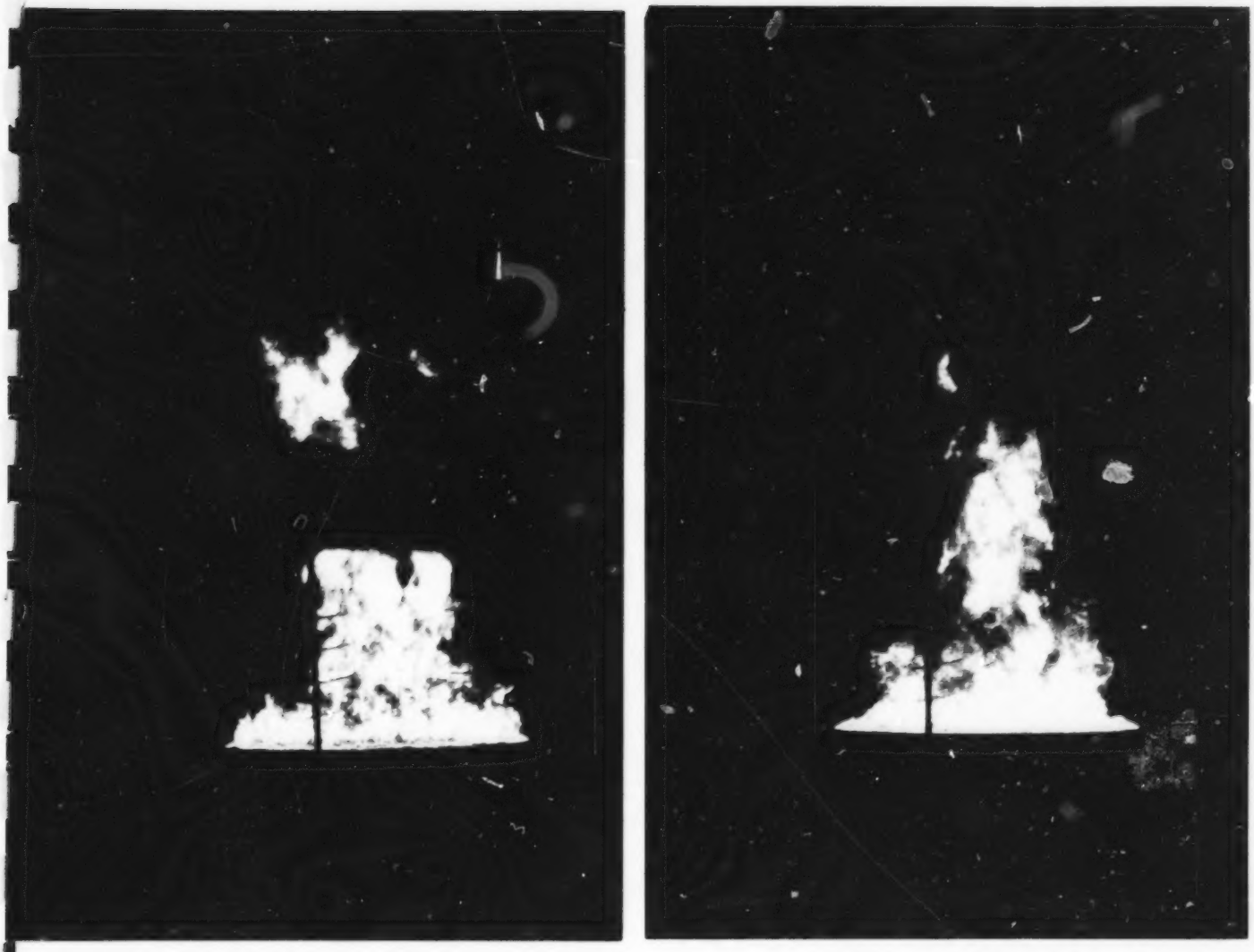


FIGURE 20
FINAL STAGES OF FULLY DEVELOPED FIRE

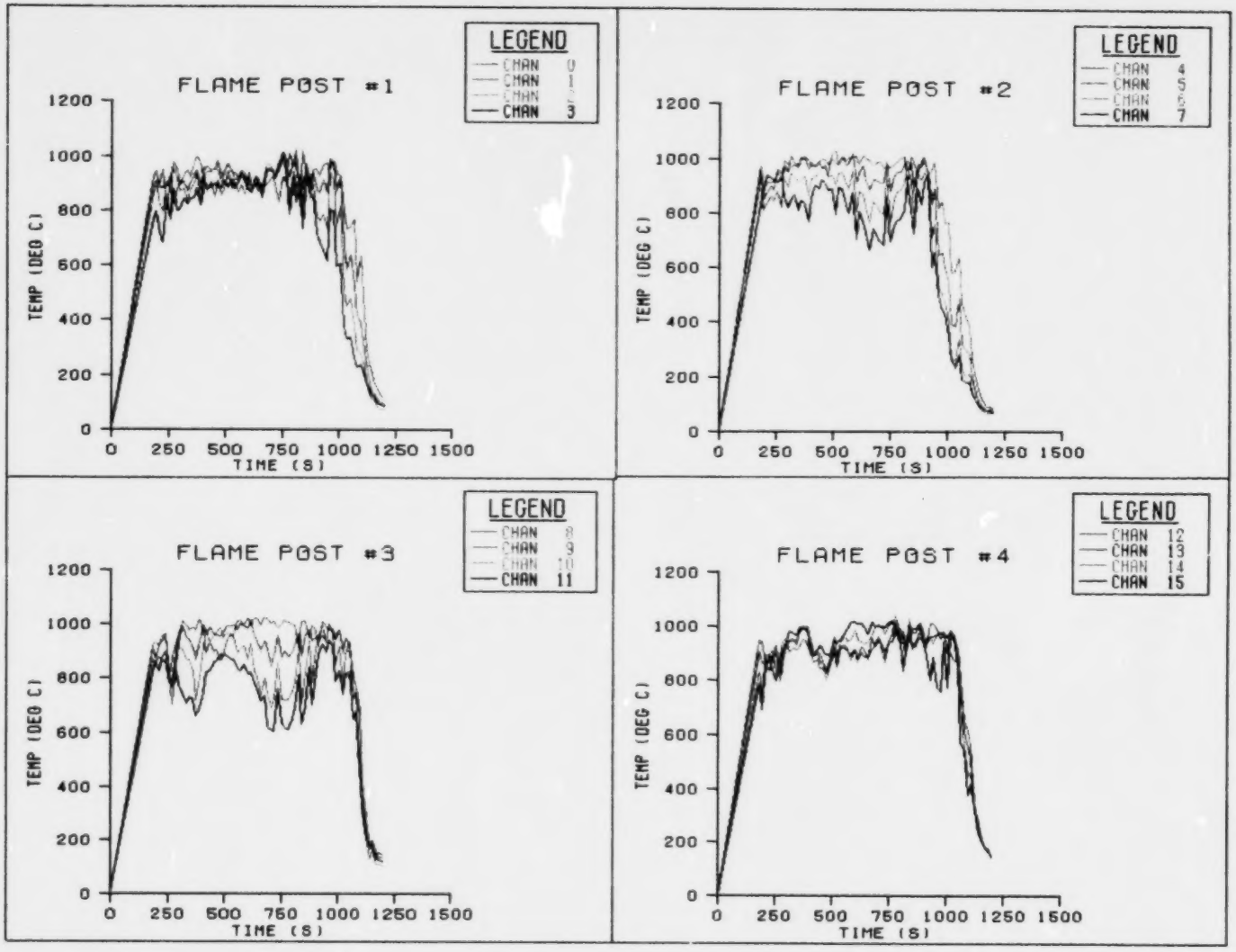


FIGURE 21

FLAME TEMPERATURES AT FOUR POSTS
(TEST WITHIN AECB REQUIREMENTS)

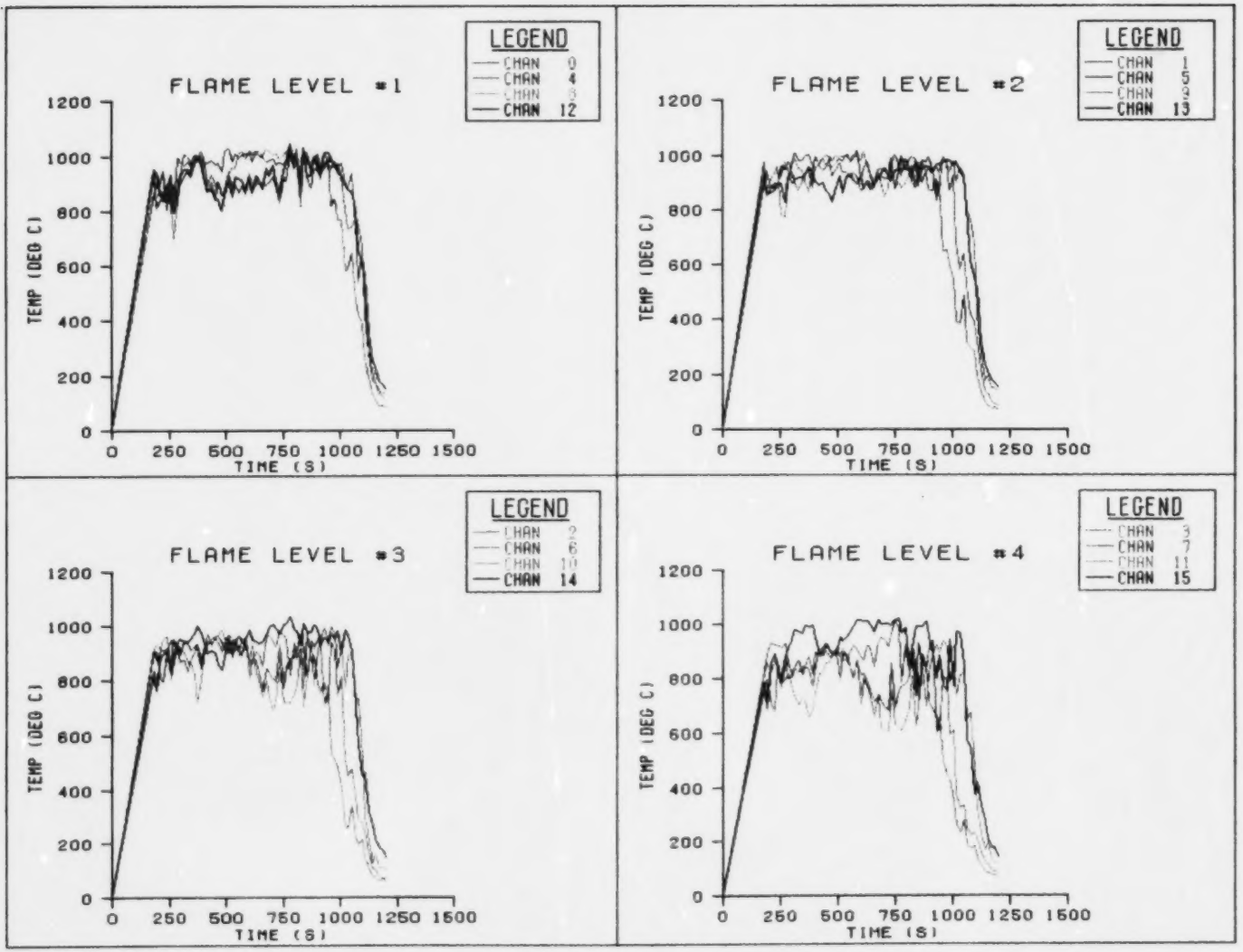


FIGURE 22

FLAME TEMPERATURES AT FOUR LEVELS
(TEST WITHIN AECB REQUIREMENTS)

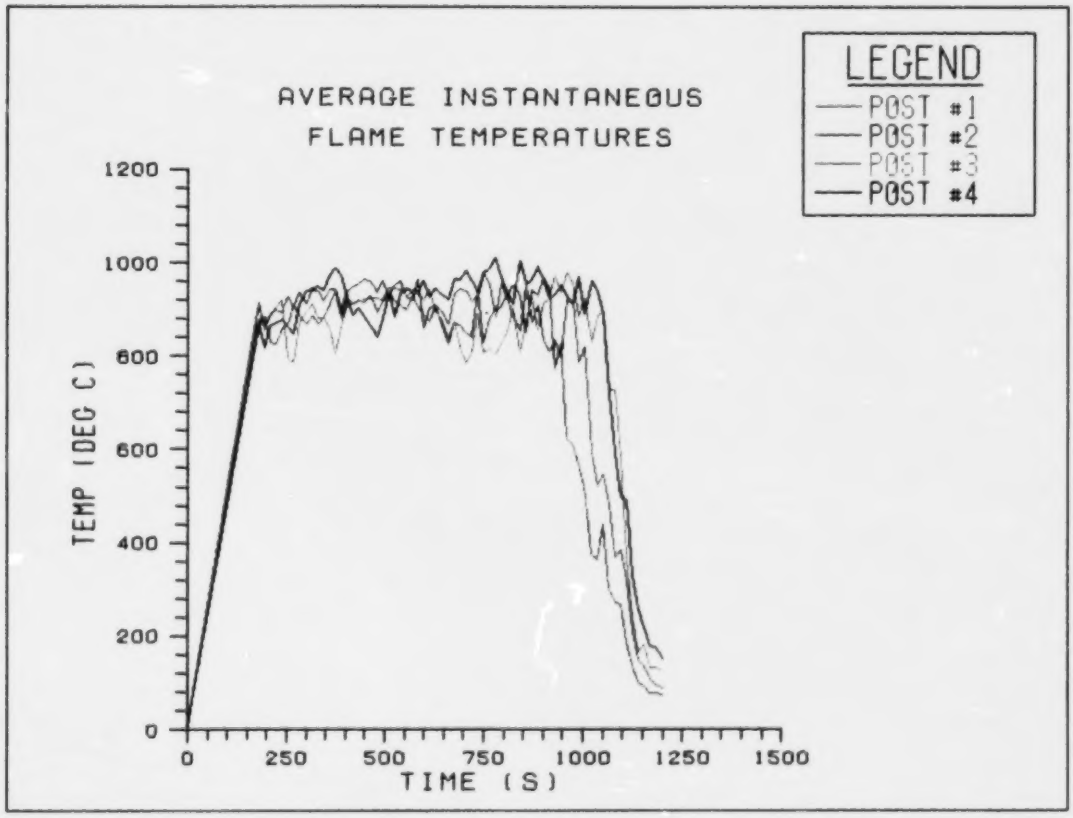


FIGURE 23

AVERAGE INSTANTANEOUS FLAME TEMPERATURES
FOR FOUR POSTS
(TEST WITHIN AECB REQUIREMENTS)

88-127
176530-RD

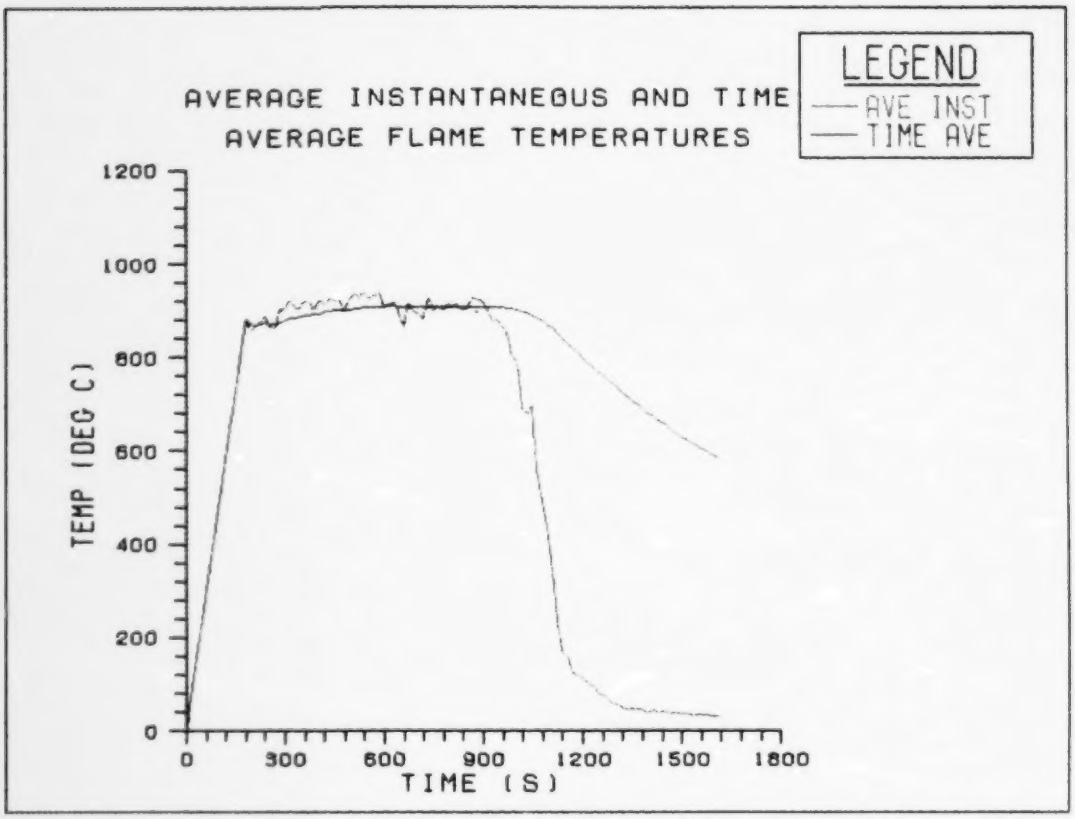


FIGURE 24

AVERAGE INSTANTANEOUS AND TIME AVERAGE FLAME TEMPERATURES
BASED ON 16 FLAME T/C'S
(TEST WITHIN AECB REQUIREMENTS)

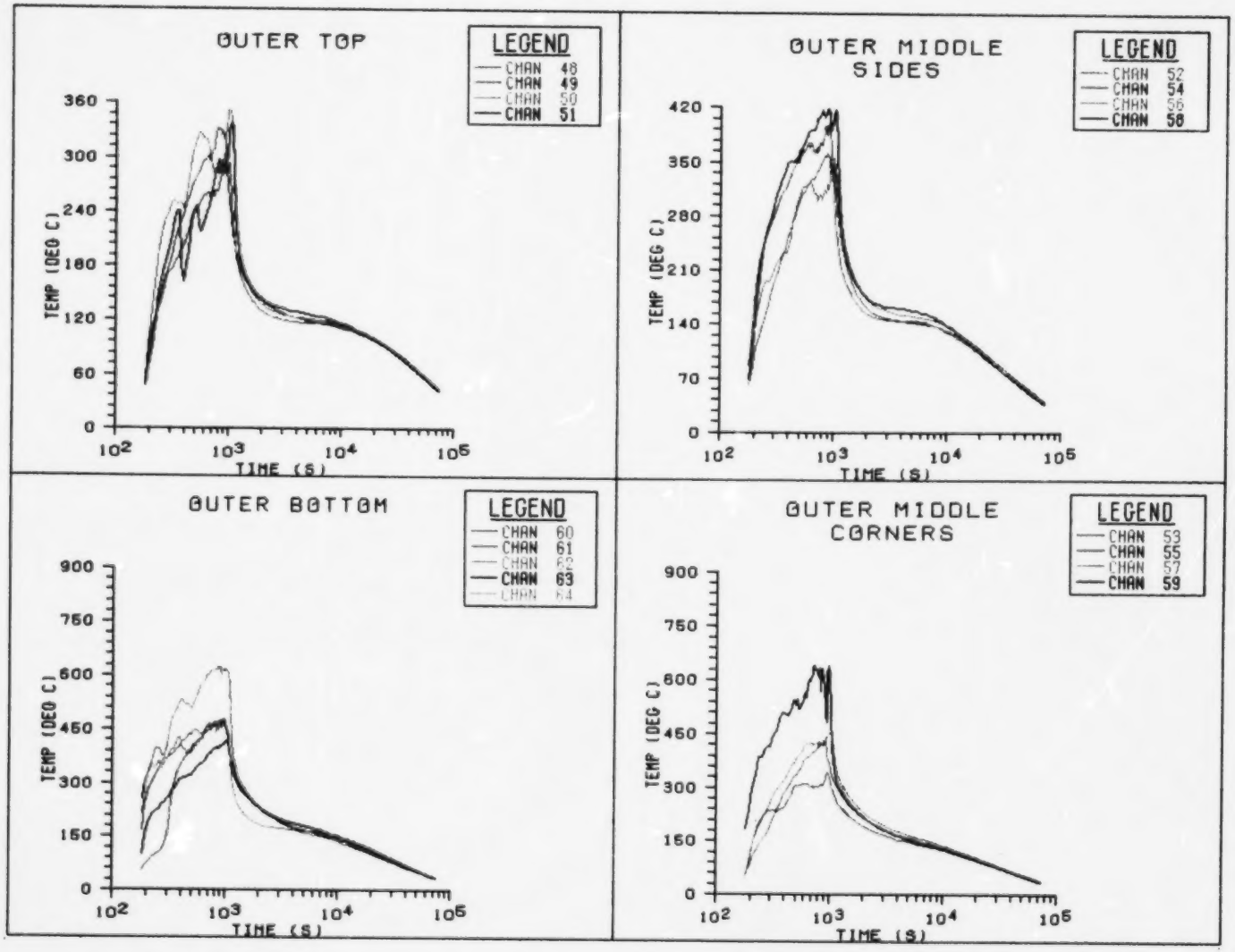


FIGURE 25

OUTER WALL TEMPERATURES
(TEST WITHIN AECB REQUIREMENTS)

88-127
176532-RD

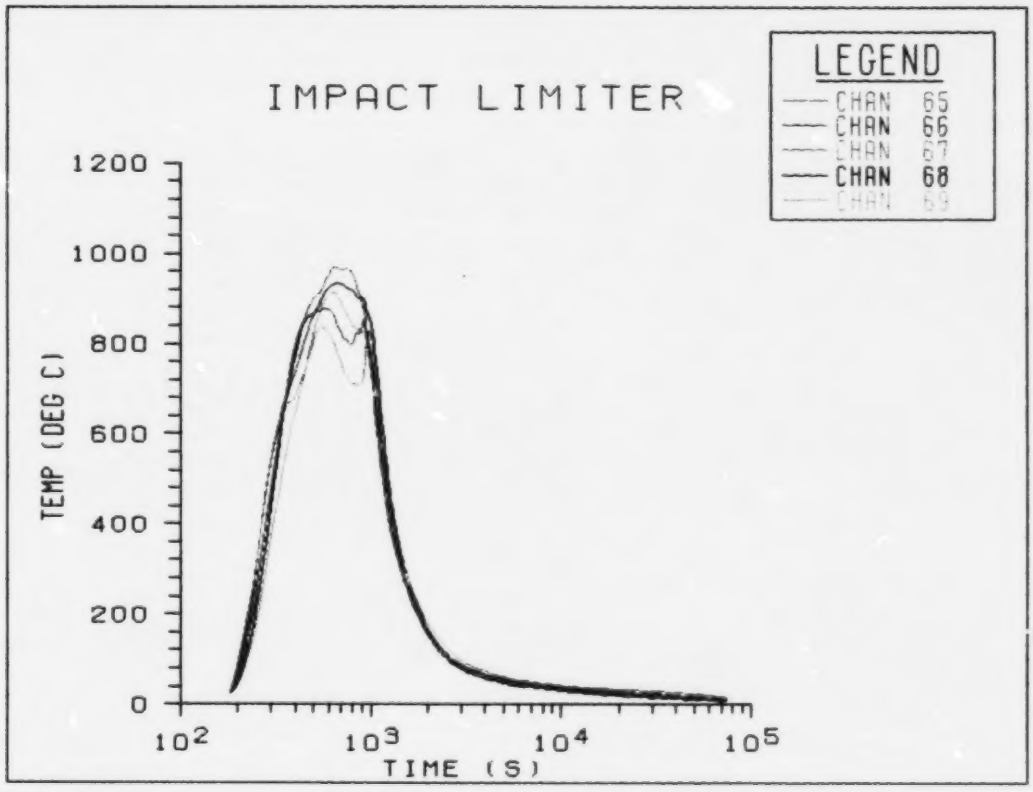


FIGURE 26

IMPACT LIMITER TEMPERATURES
(TEST WITHIN AECB REQUIREMENTS)

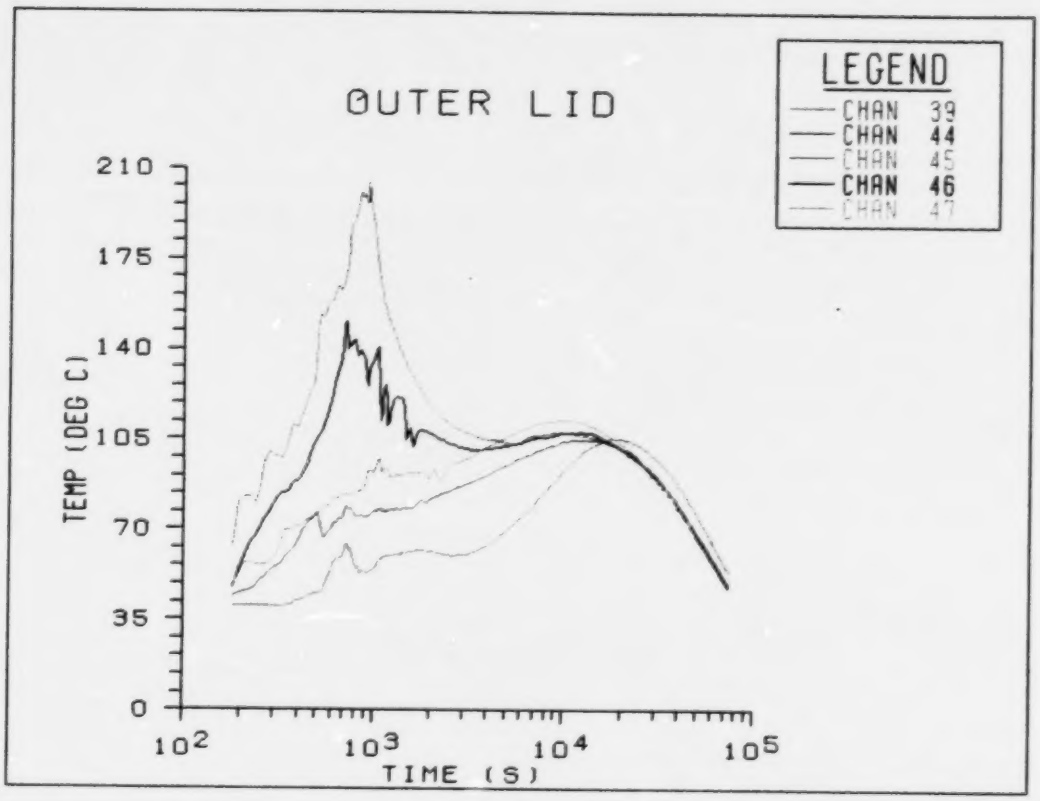


FIGURE 27

OUTER LID TEMPERATURES
(TEST WITHIN AECB REQUIREMENTS)

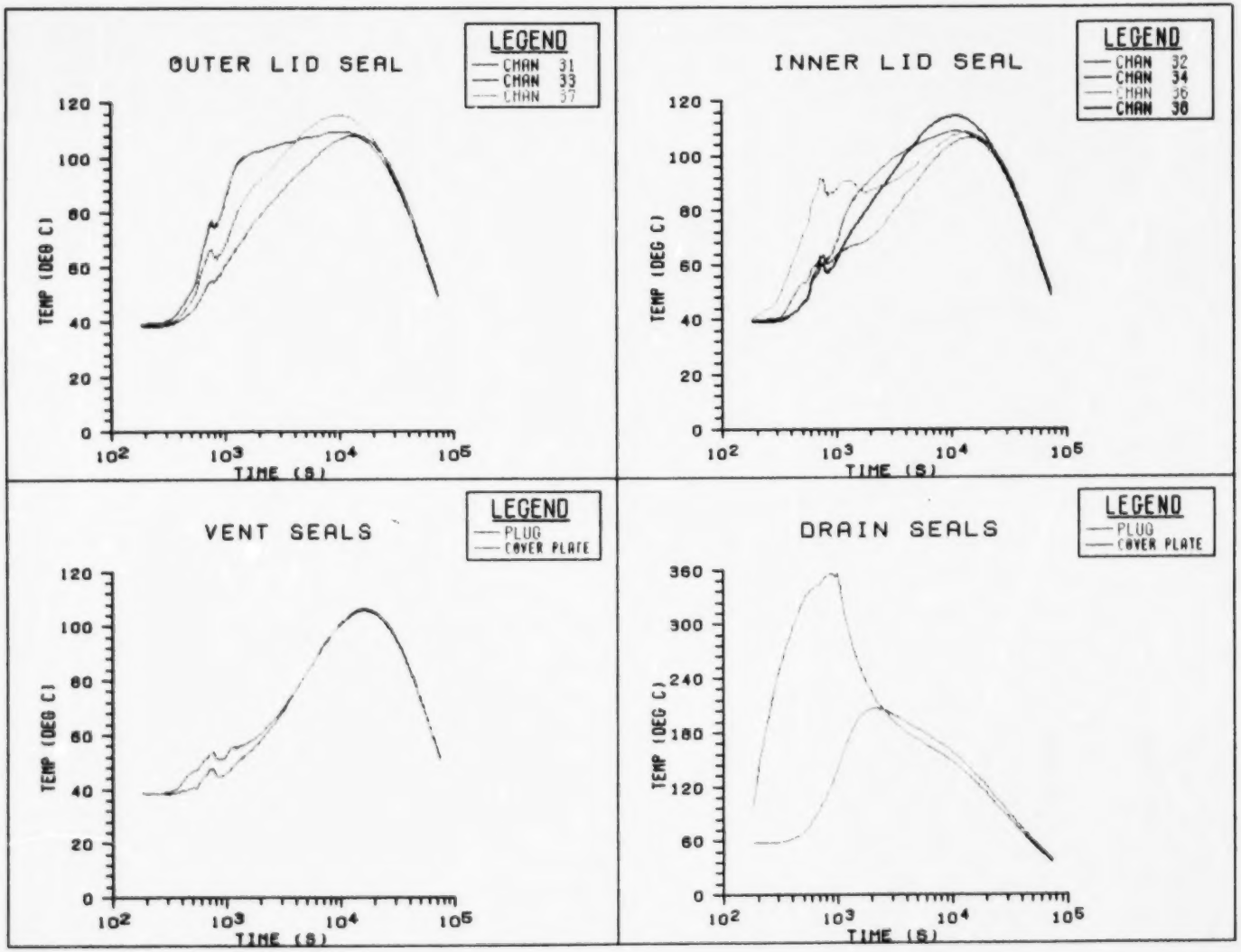


FIGURE 28

SEAL TEMPERATURES
(TEST WITHIN AECB REQUIREMENTS)

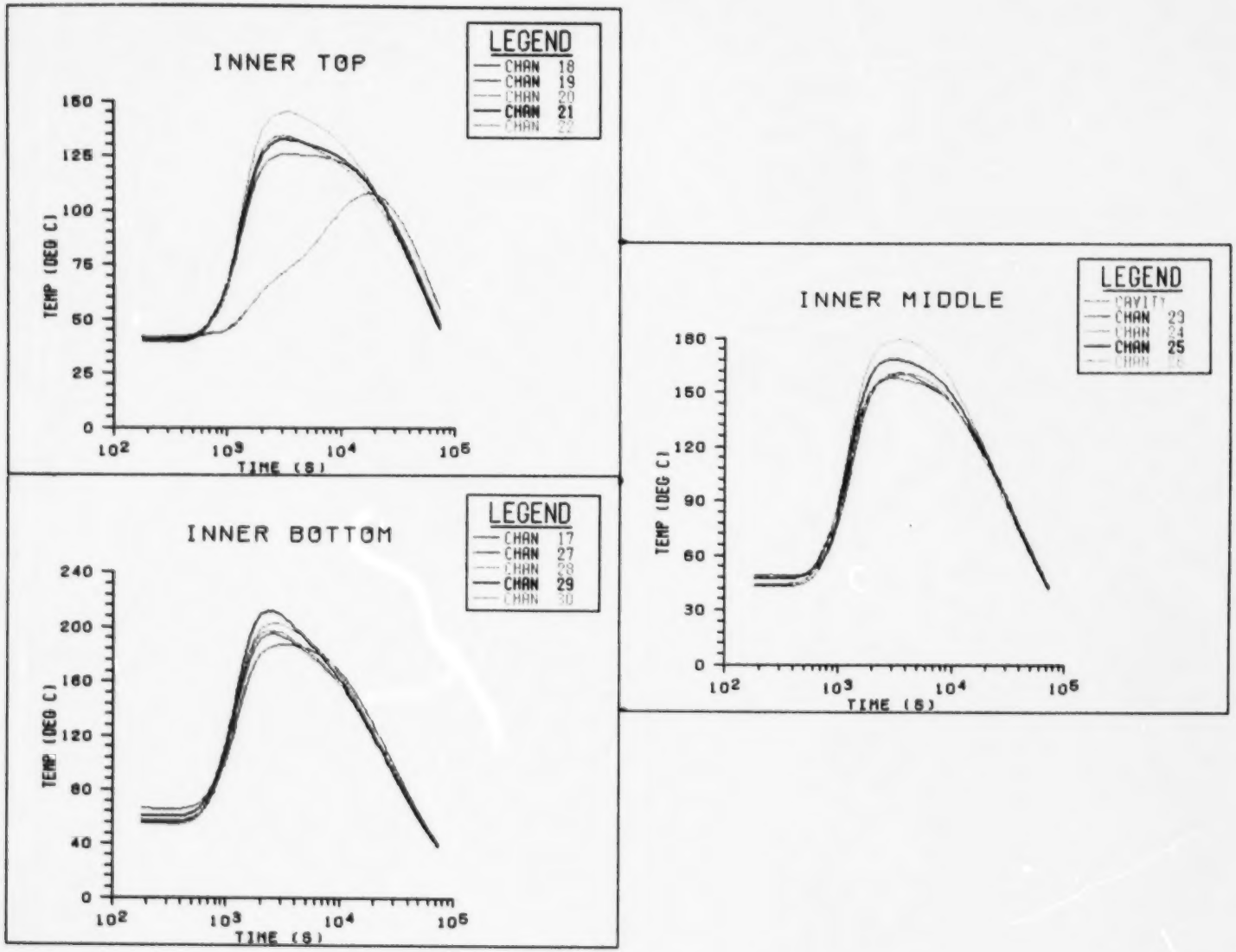


FIGURE 29

INNER WALL AND CAVITY TEMPERATURES
(TEST WITHIN AECB REQUIREMENTS)

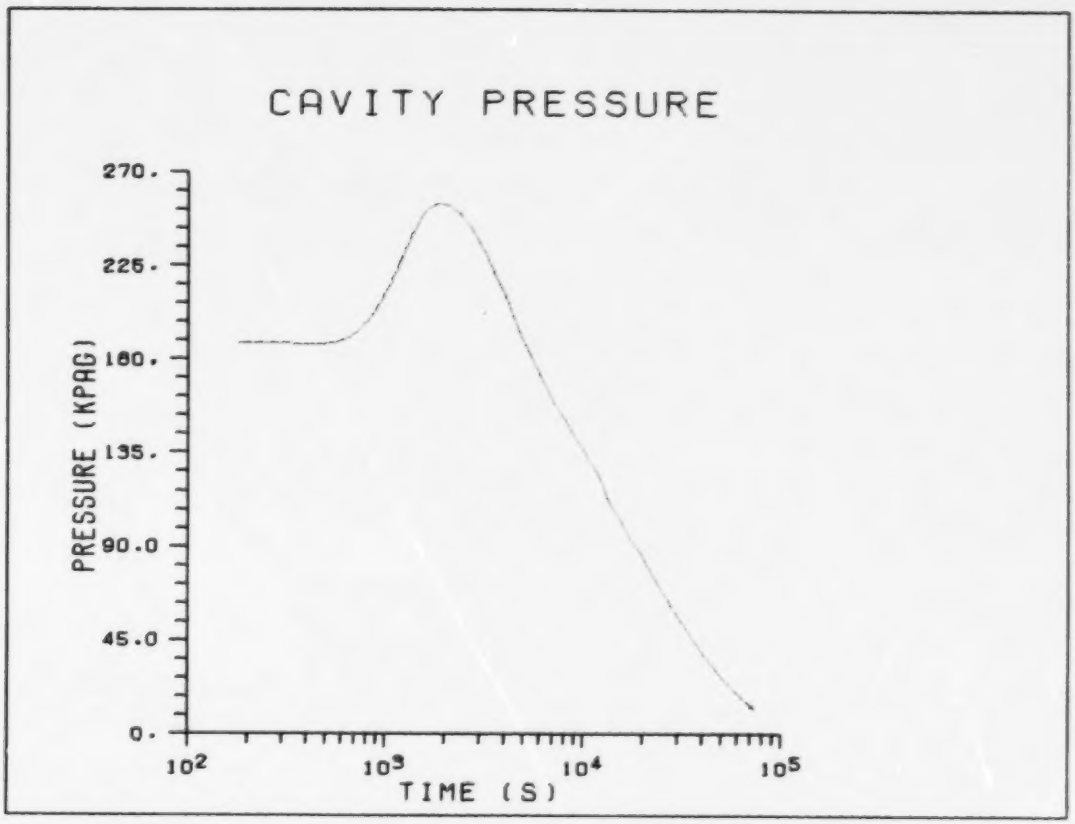


FIGURE 30

CAVITY PRESSURE
(TEST WITHIN AECB REQUIREMENTS)

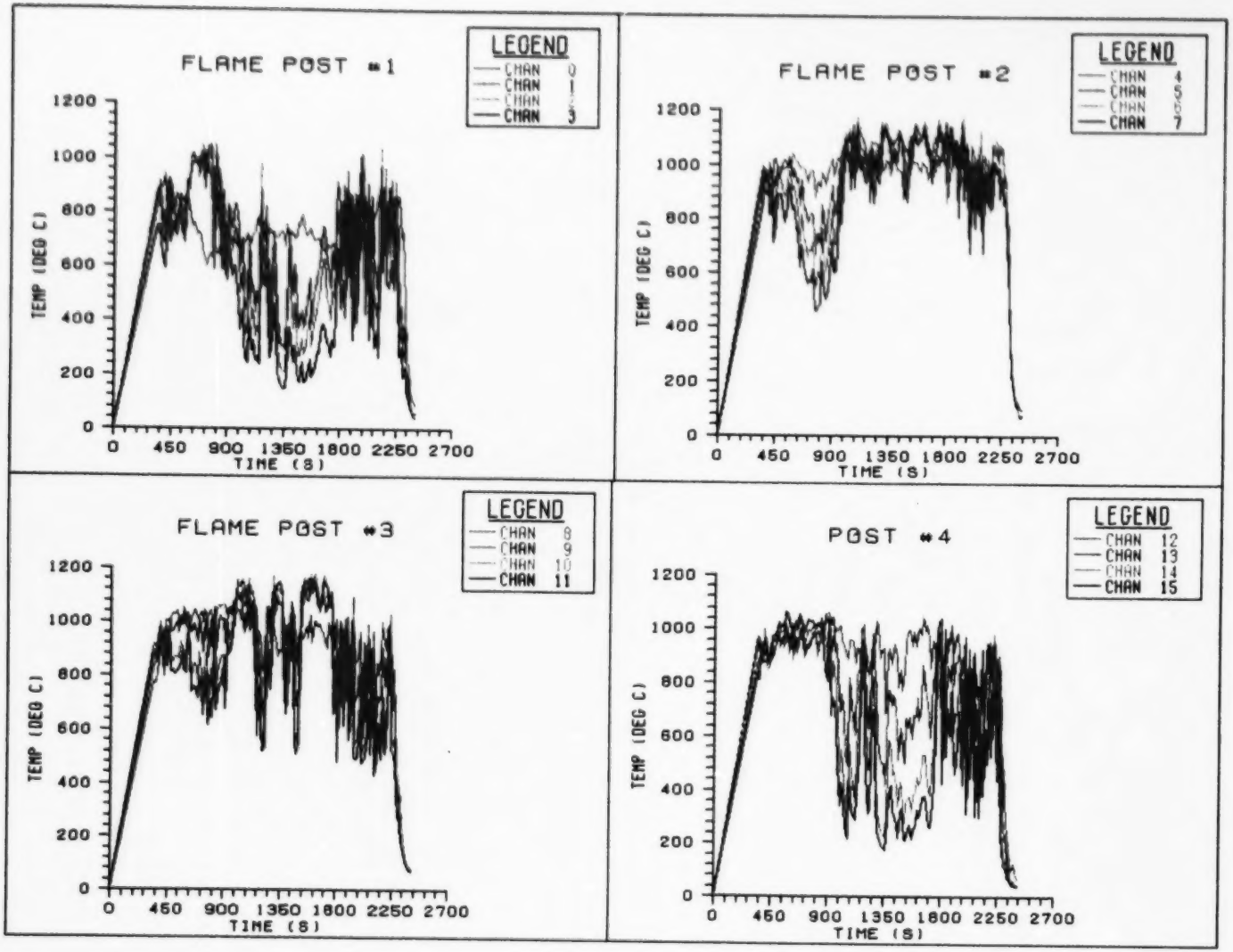


FIGURE 31

FLAME TEMPERATURES AT FOUR POSTS
(TEST BEYOND AECB REQUIREMENTS)

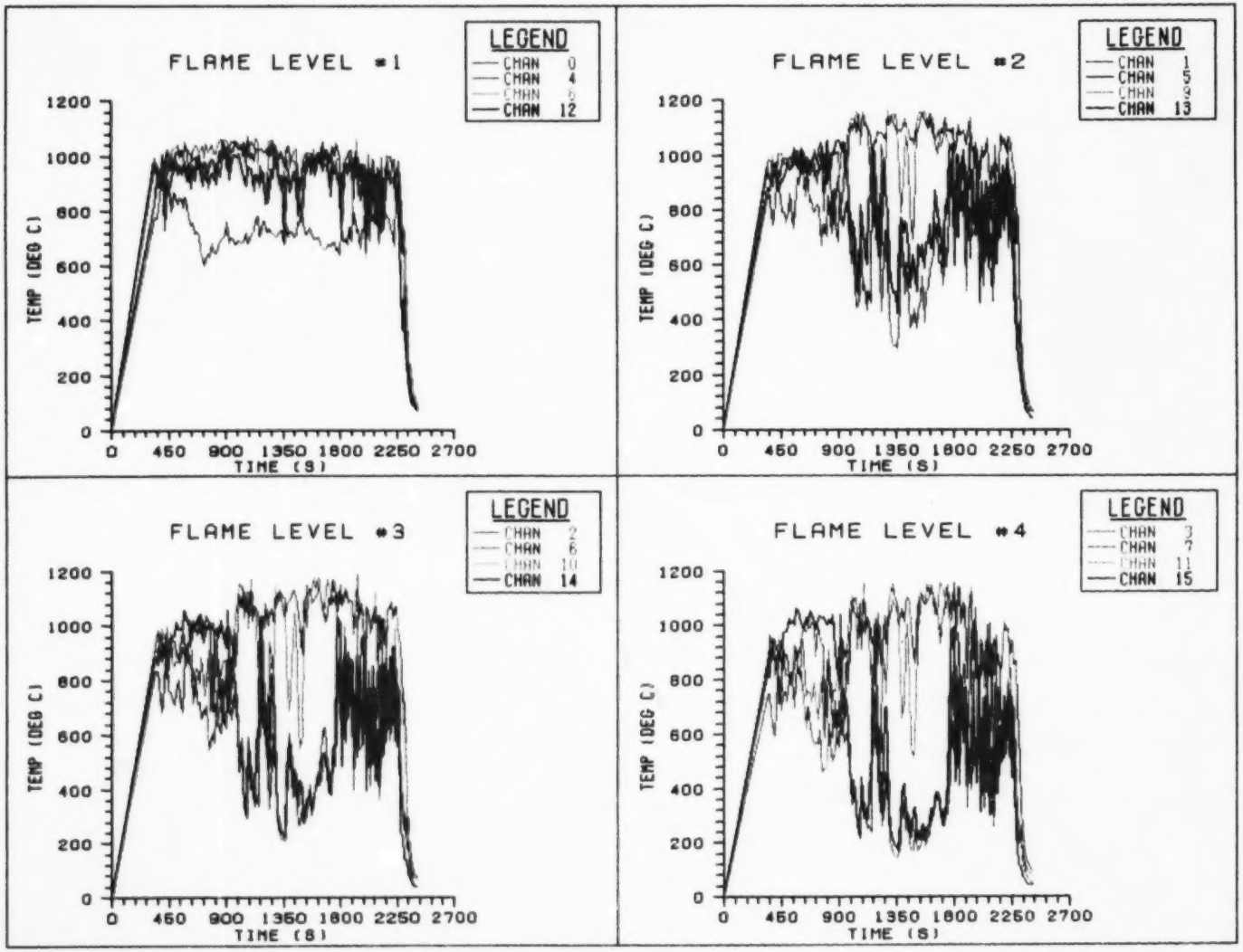


FIGURE 32

FLAME TEMPERATURES AT FOUR LEVELS
(TEST BEYOND AECB REQUIREMENTS)

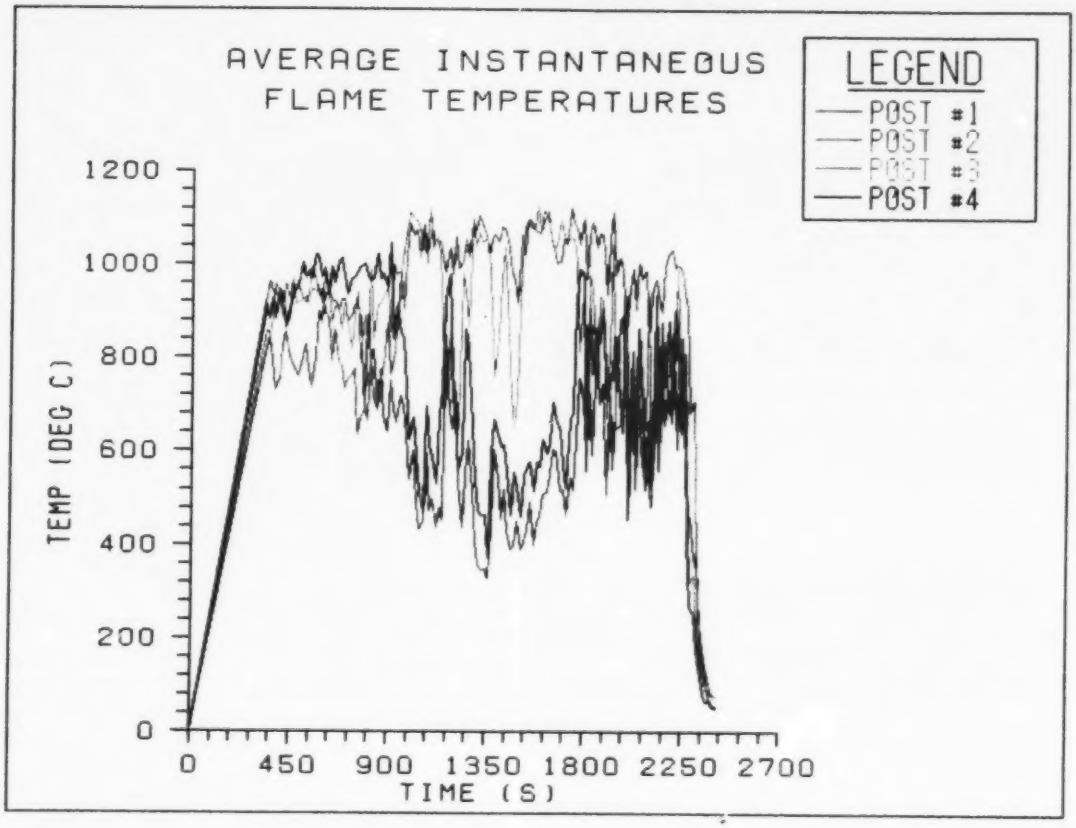


FIGURE 33

AVERAGE INSTANTANEOUS FLAME TEMPERATURES FOR FOUR POSTS (TEST BEYOND AECB REQUIREMENTS)

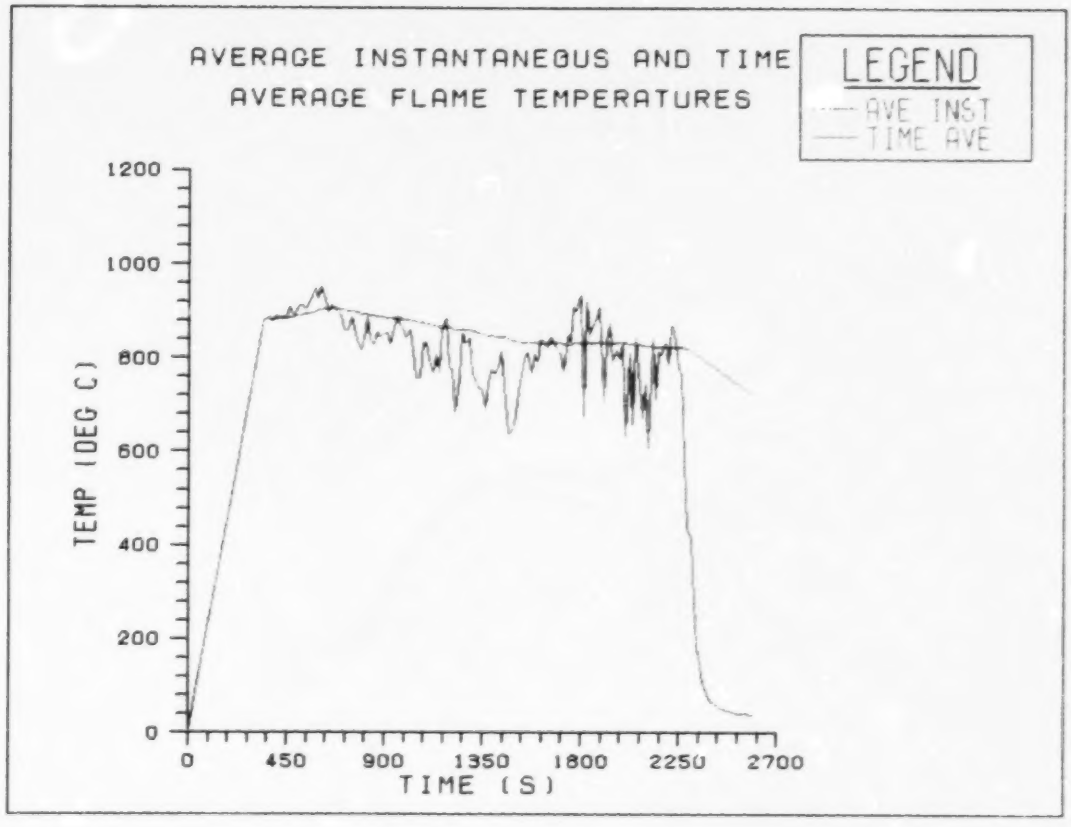


FIGURE 34

AVERAGE INSTANTANEOUS AND TIME AVERAGE FLAME TEMPERATURES
BASED ON 16 FLAME T/C'S
(TEST BEYOND AECB REQUIREMENTS)

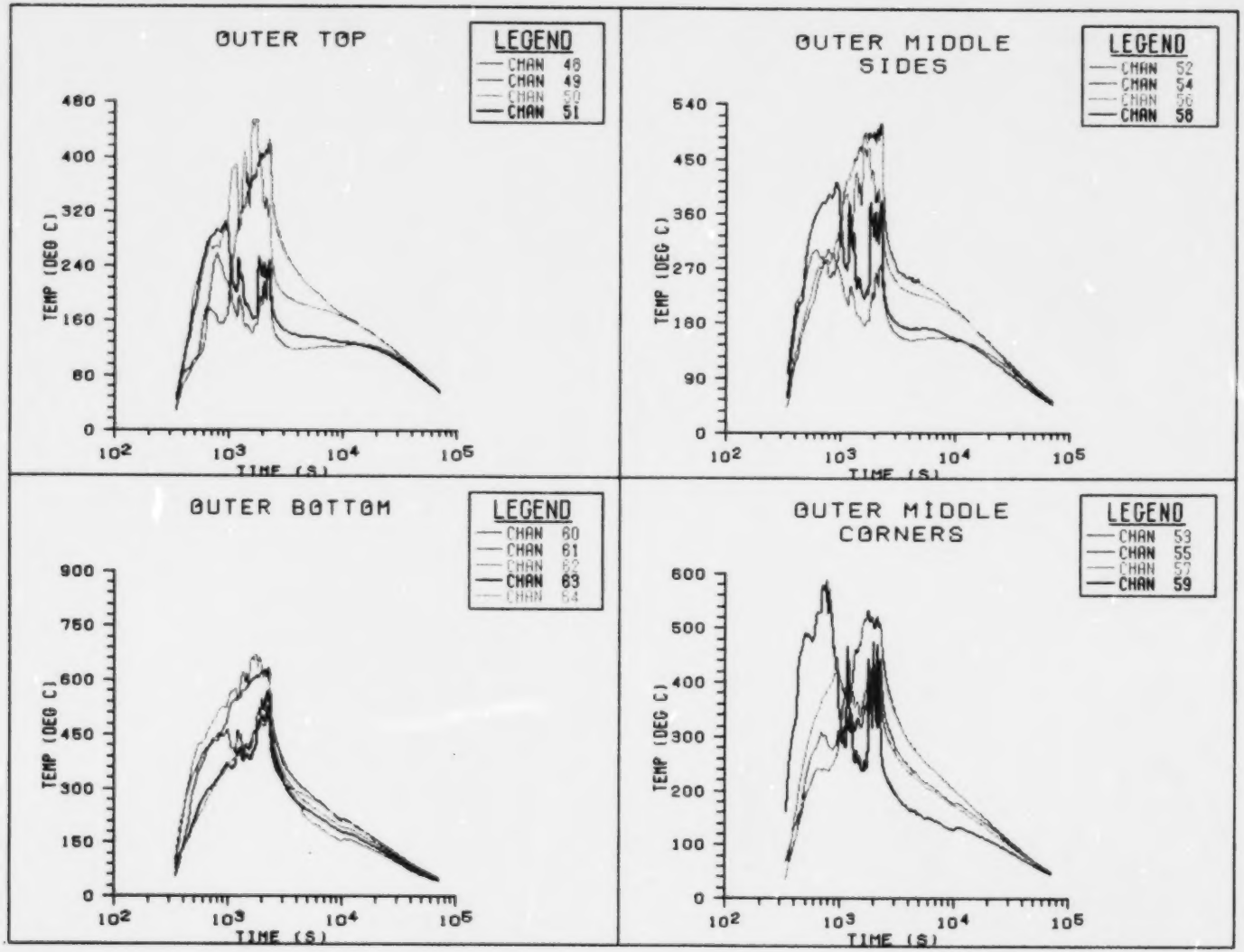


FIGURE 35

OUTER WALL TEMPERATURES
(TEST BEYOND AECB REQUIREMENTS)

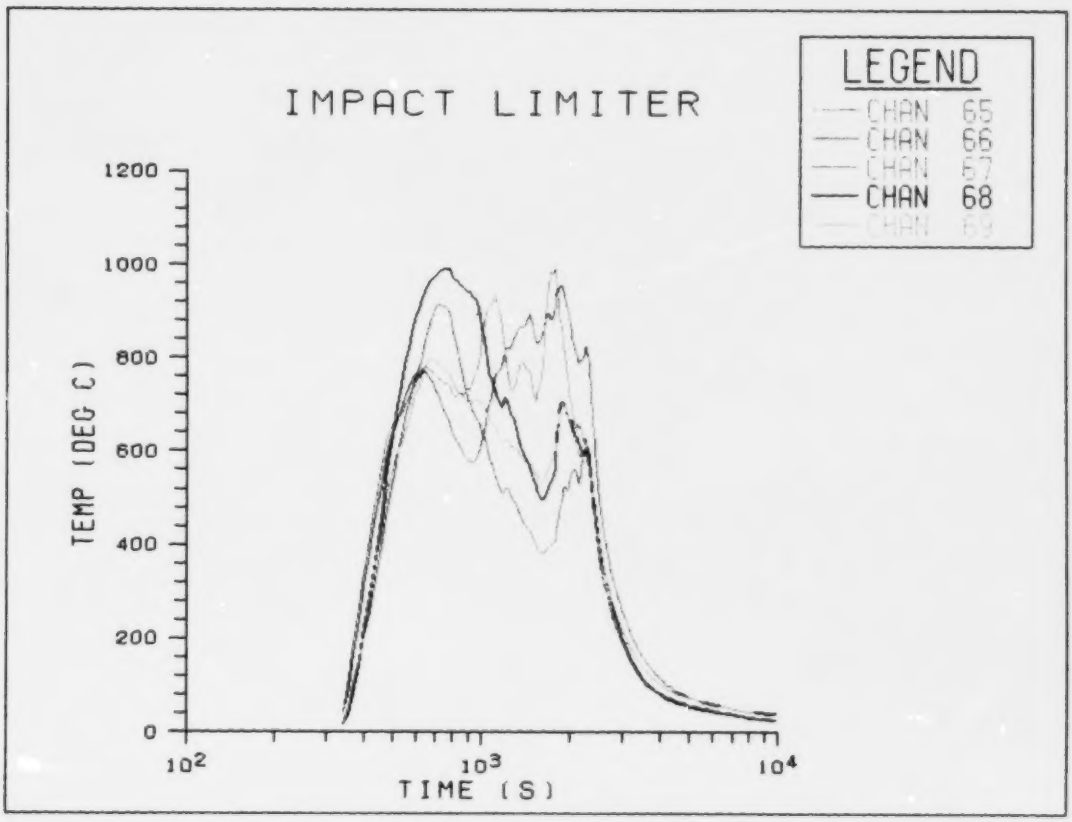


FIGURE 36

IMPACT LIMITER TEMPERATURES
(TEST BEYOND AECB REQUIREMENTS)

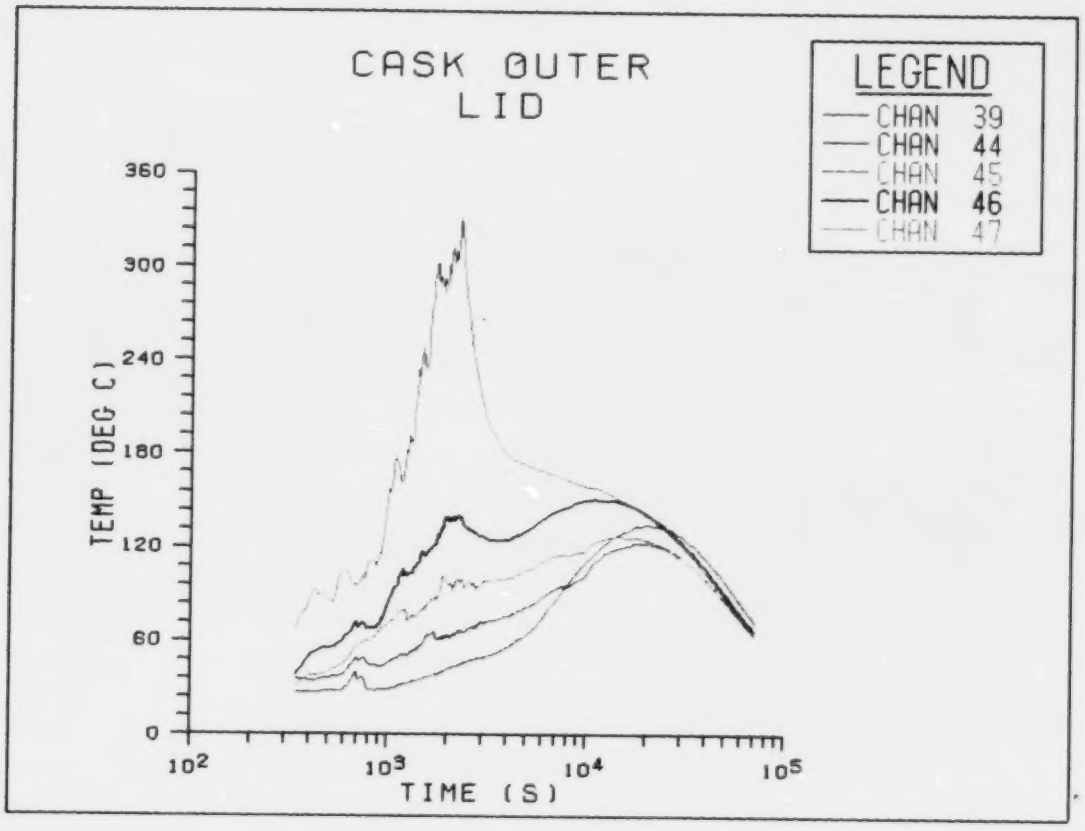


FIGURE 37

OUTER LID TEMPERATURES
(TEST BEYOND AECB REQUIREMENTS)

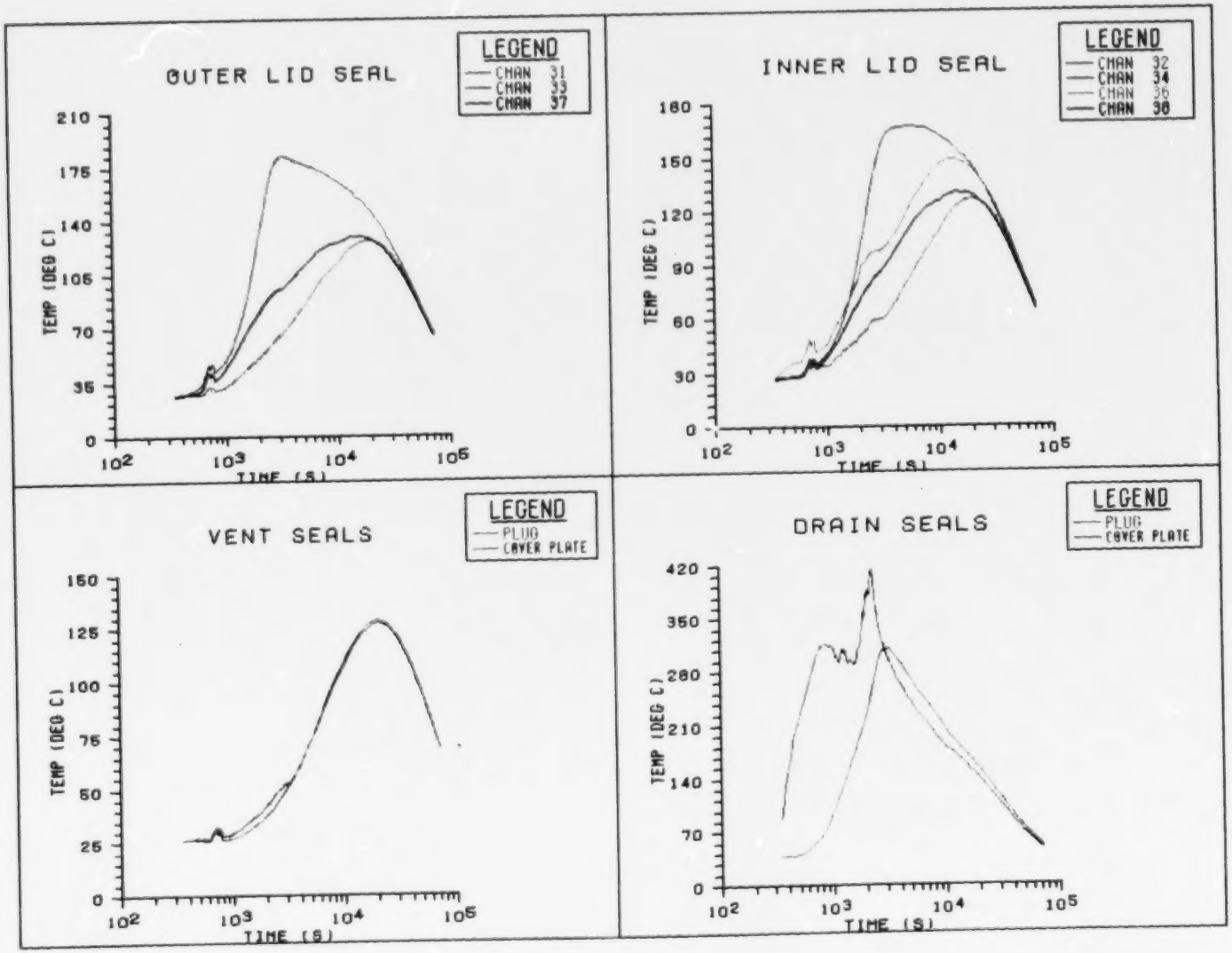


FIGURE 38

SEAL TEMPERATURES
(TEST BEYOND AECB REQUIREMENTS)

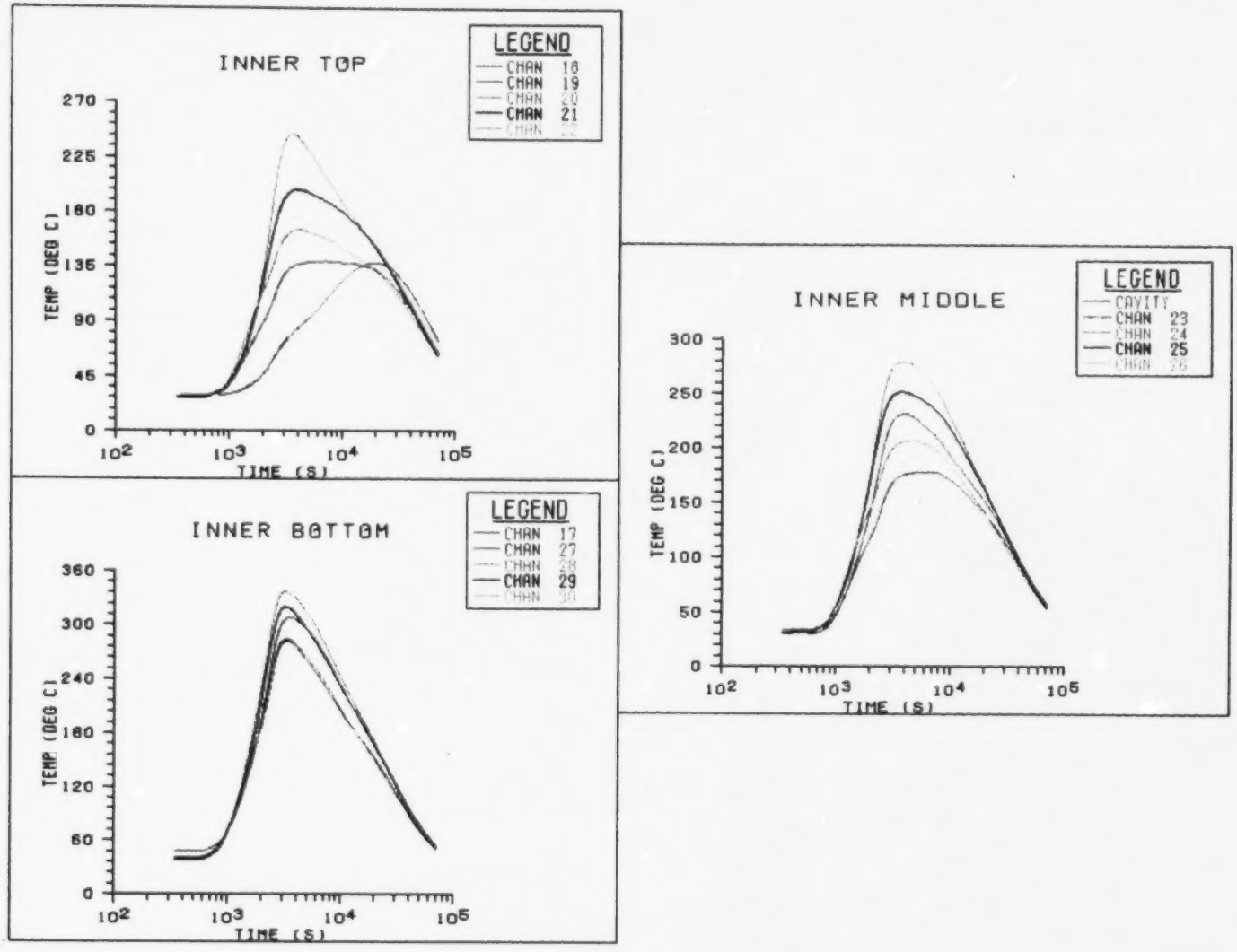


FIGURE 39

INNER WALL AND CAVITY TEMPERATURES
(TEST BEYOND AECB REQUIREMENTS)

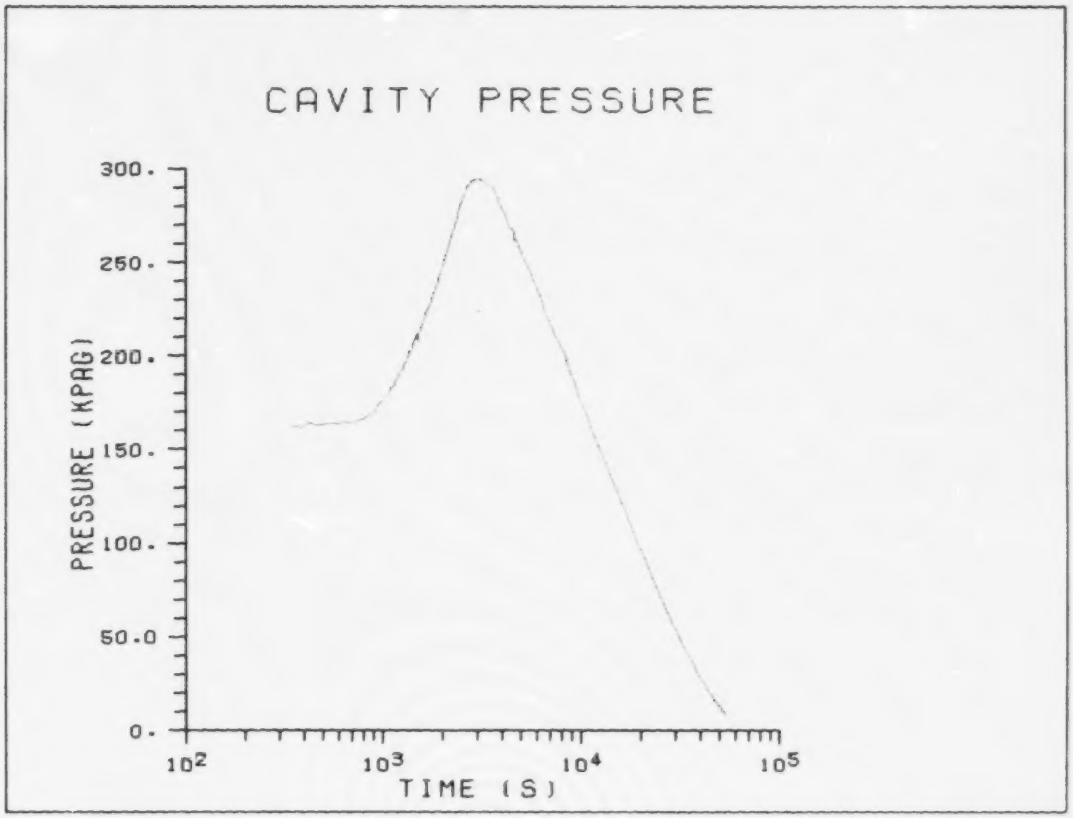


FIGURE 40

CAVITY PRESSURE
(TEST BEYOND AECB REQUIREMENTS)

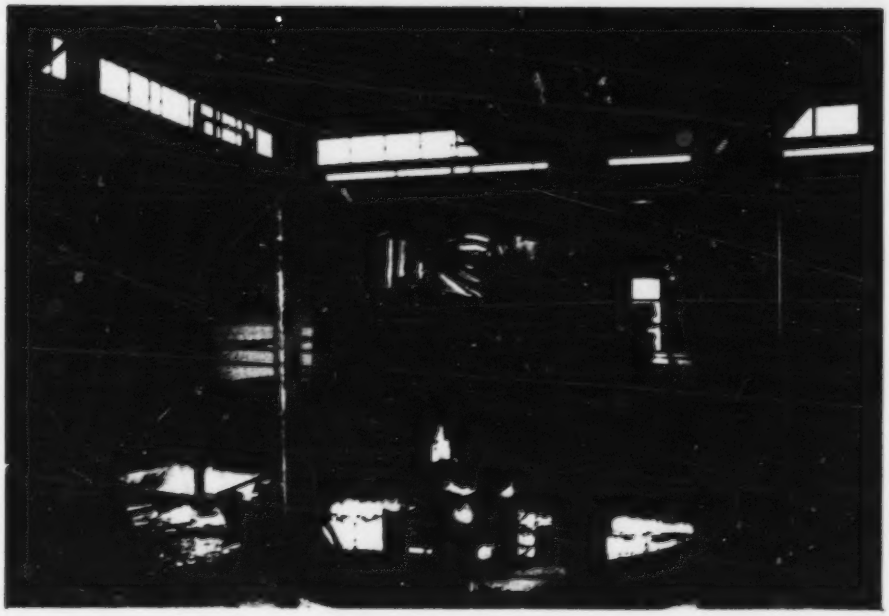
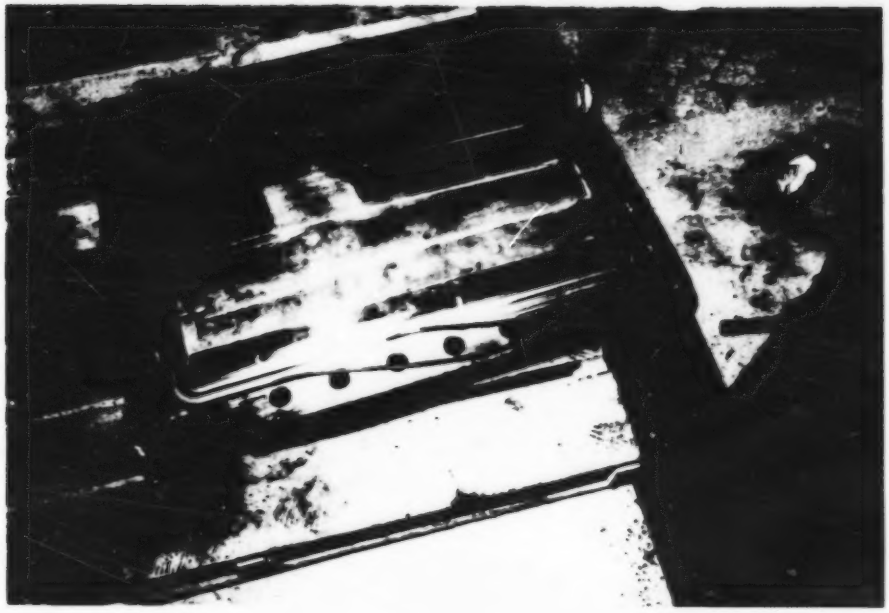


FIGURE 41

EXPERIMENTAL SET UP AFTER
TEST BEYOND AECB REQUIREMENTS



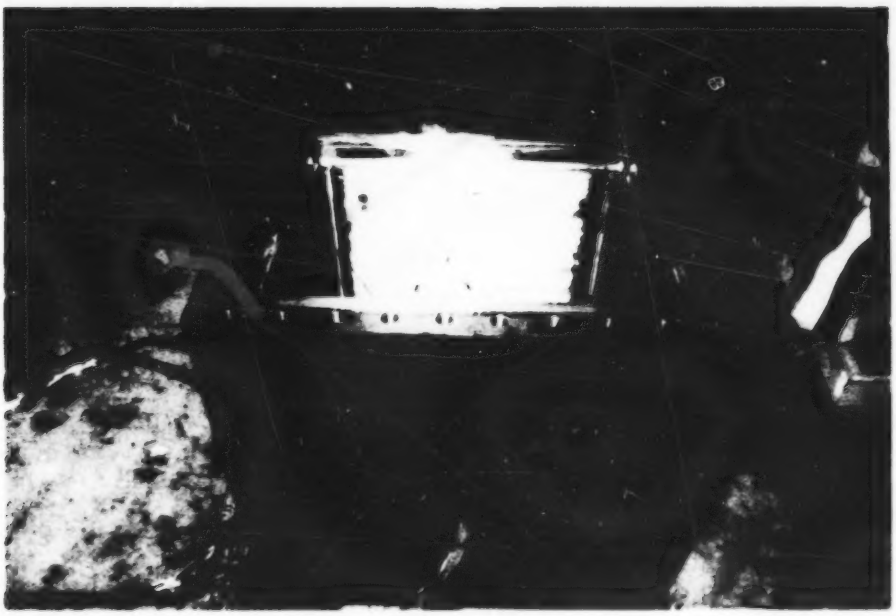


FIGURE 42
CASK MODEL OPENED FOR EXAMINATION

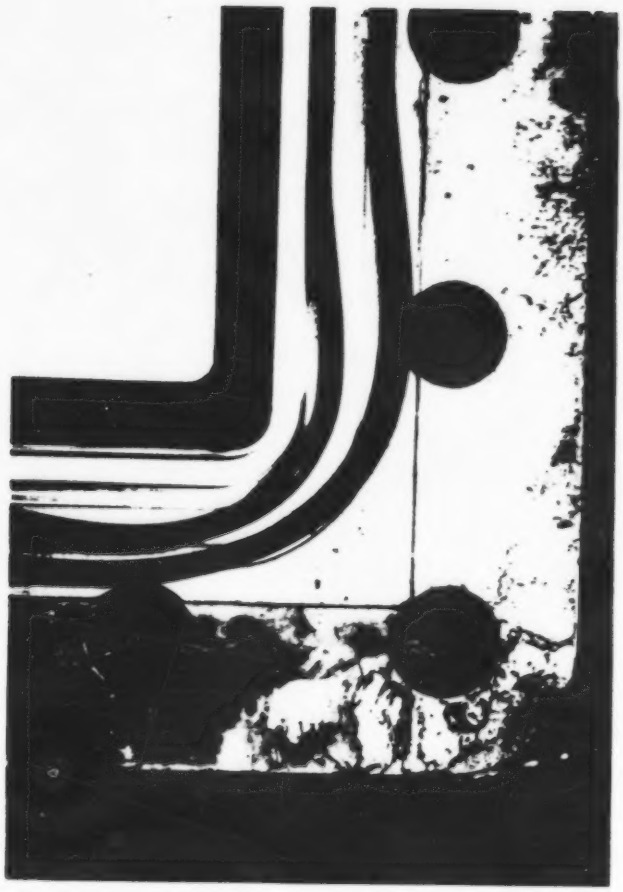
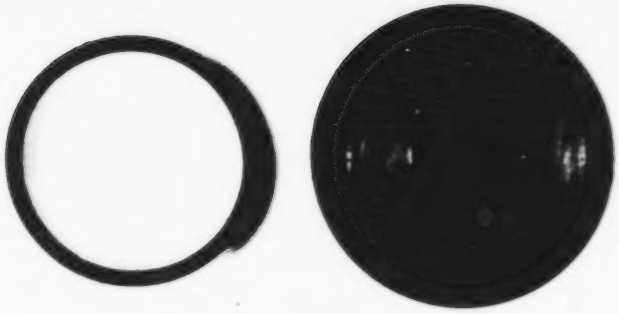
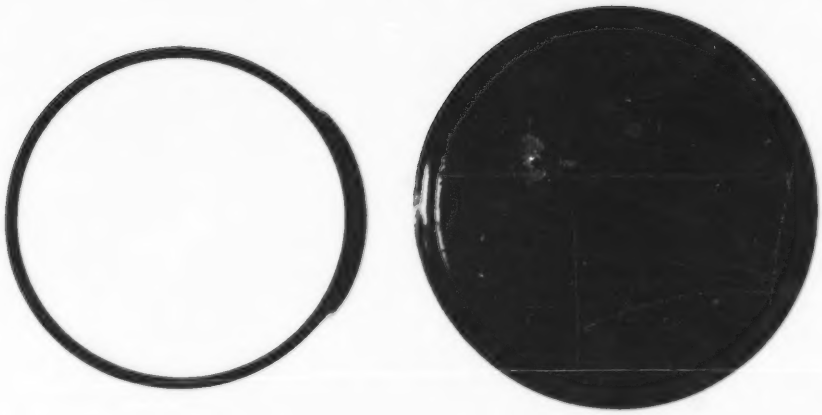


FIGURE 43

EXAMINATION OF LID SEALS
AFTER TEST BEYOND AECB REQUIREMENTS



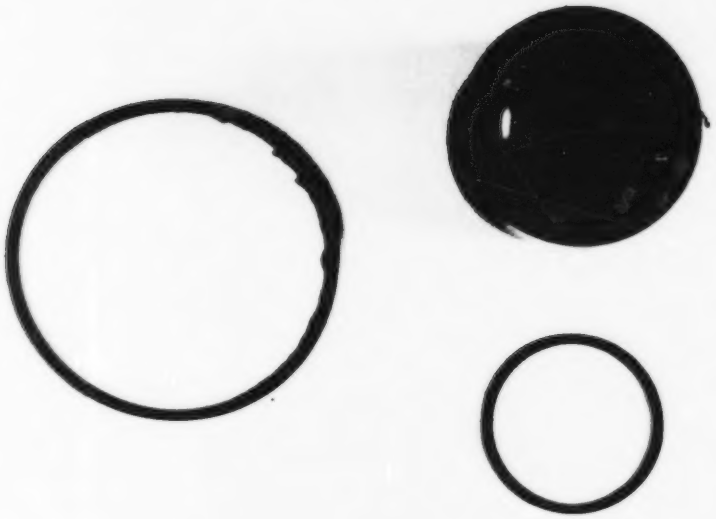
Plug



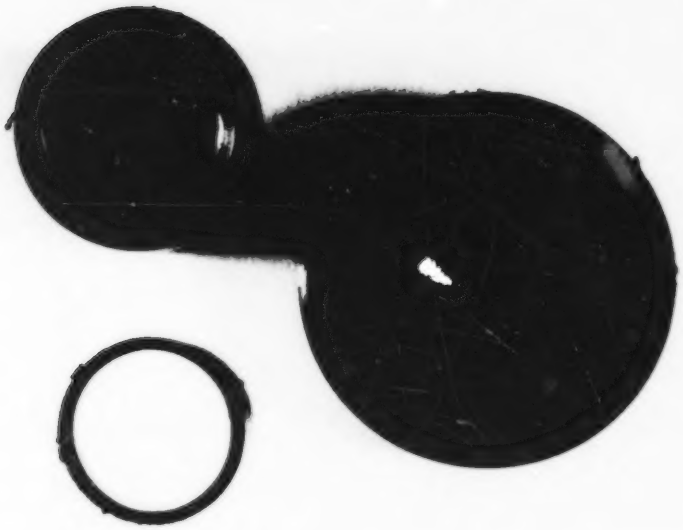
Cover Plate

FIGURE 44

EXAMINATION OF VENT SEALS
AFTER TEST BEYOND AECB REQUIREMENTS



After Test Within AECB Requirements



After Test Beyond AECB Requirements

FIGURE 45

EXAMINATION OF DRAIN SEALS
AFTER TESTS WITHIN AND BEYOND AECB REQUIREMENTS

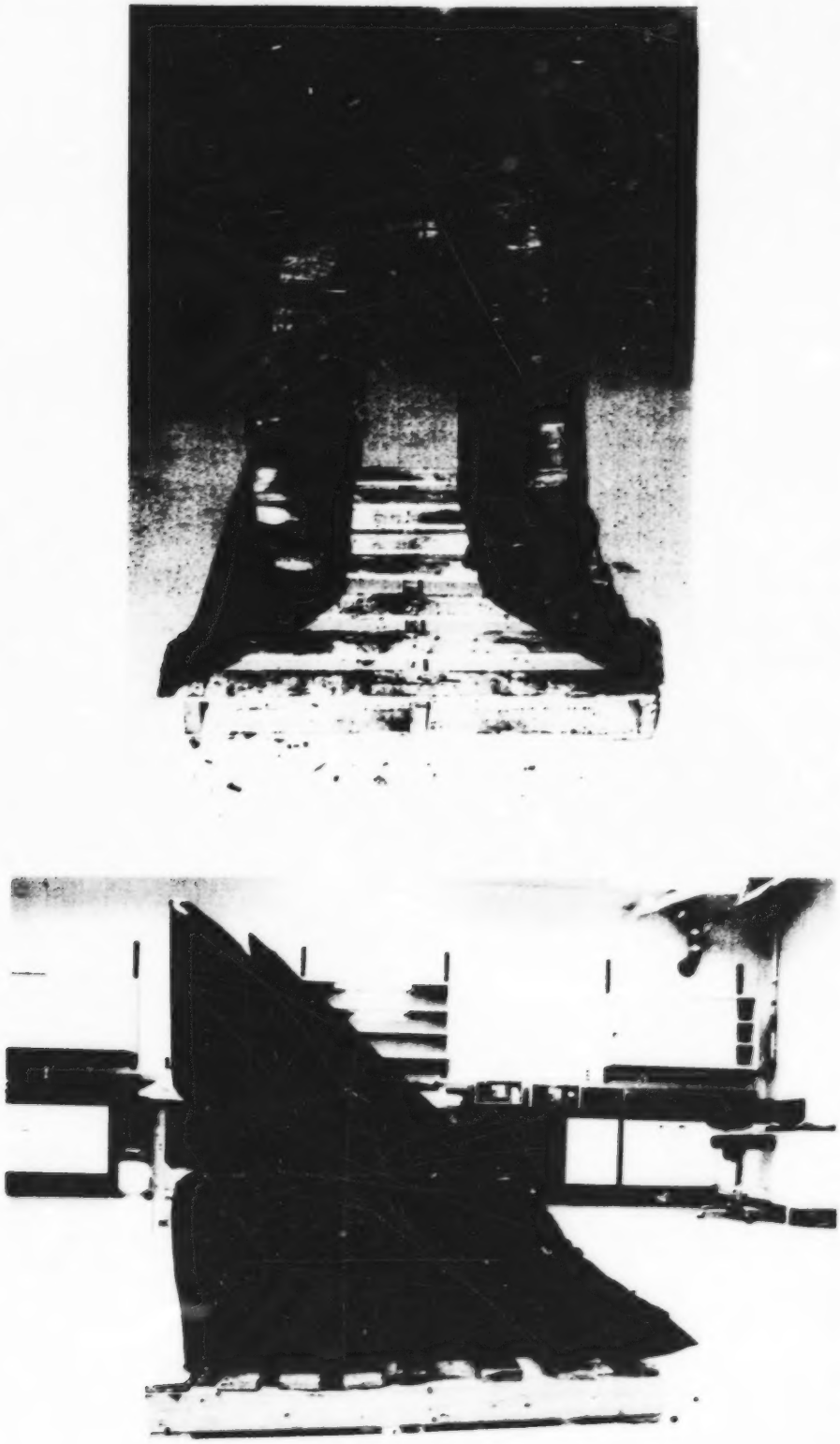


FIGURE 46
IMPACT LIMITER CUT DIAGONALLY FOR EXAMINATION

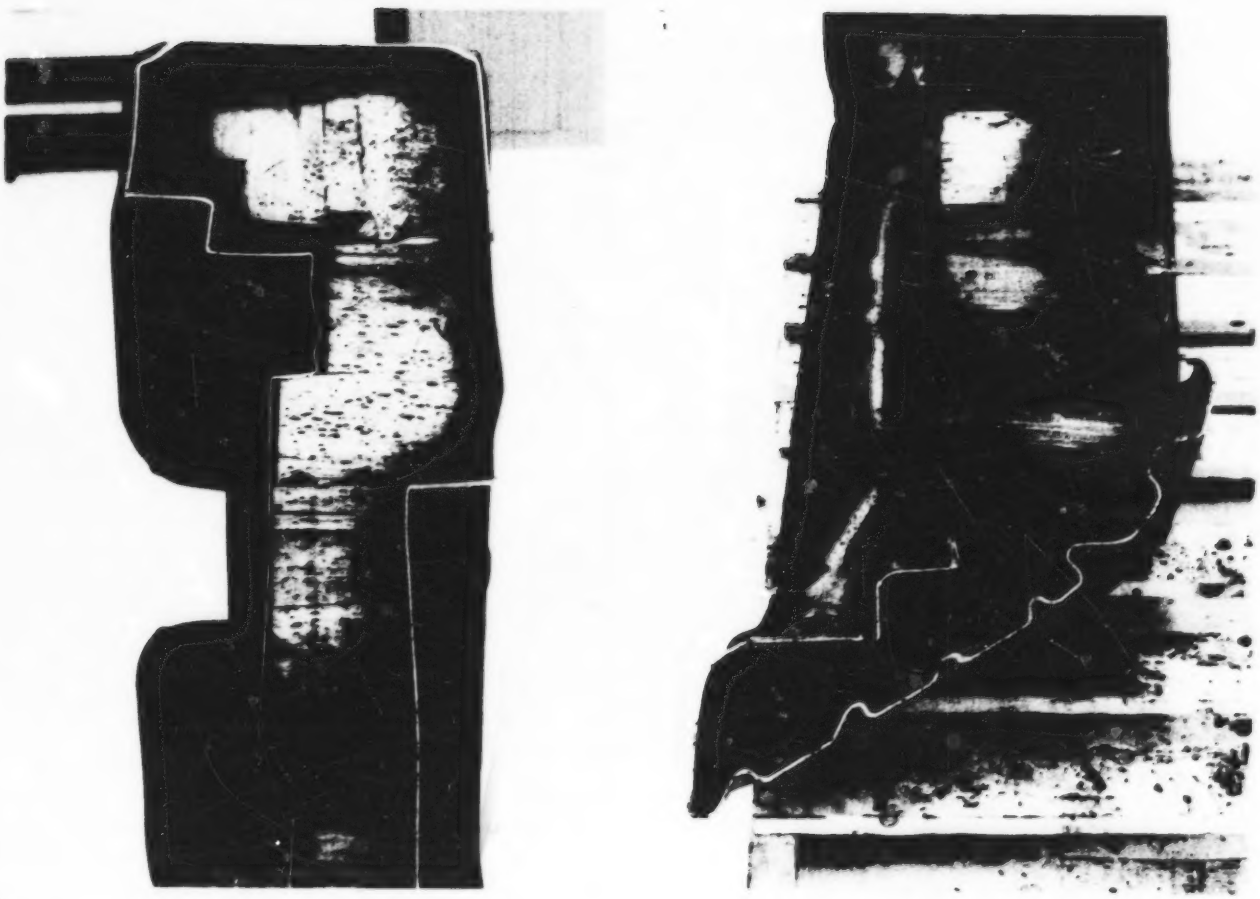


FIGURE 47

CLOSE UP PHOTOGRAPH OF ONE IMPACT LIMITER SECTION
FOR EXAMINATION

TABLE 1

SUMMARY OF RESULTS
(TEST WITHIN AECB REQUIREMENTS)

RESULTS DESCRIPTION	TEMPERATURE (°C)	* TIME (s)
Average Instantaneous Flame Temperature	860 to 940	- -
Time Average of Flame Temperature	860 to 900	- -
Maximum Cavity Air Temperature	160	3,500
Maximum Inner Lid Seal Temperature	114	10,000
Maximum Outer Lid Seal Temperature	114	10,000
Maximum Vent Seal Temperature (Cover Plate)	106	18,000
Maximum Vent Seal Temperature (Plug)	106	18,000
Inside Lid Temperature (at Centre)	107	20,000
Outside Lid Temperature (at Centre)	105	20,000
Maximum Drain Seal Temperature (Cover Plate)	354	1,000
Maximum Drain Seal Temperature (Plug)	204	2,000
Maximum Cask Outer Surface Temperature	645	700
Maximum Impact Limiter Temperature	960	700
Cavity Pressure Rise, (kPa) g	69	2,000

* Approximate Time from Start of Fire

TABLE 2

SUMMARY OF RESULTS
(TEST BEYOND AECB REQUIREMENTS - EXTENDED DURATION)

RESULTS DESCRIPTION	TEMPERATURE (°C)	* TIME (s)
Average Instantaneous Flame Temperature	600 to 940	- -
Time Average of Flame Temperature	810 to 900	- -
Maximum Cavity Air Temperature	225	4,000
Maximum Inner Lid Seal Temperature	165	6,000
Maximum Outer Lid Seal Temperature	180	3,200
Maximum Vent Seal Temperature (Cover Plate)	125	20,000
Maximum Vent Seal Temperature (Plug)	128	20,000
Inside Lid Temperature (at Centre)	135	20,000
Outside Lid Temperature (at Centre)	132	20,000
Maximum Drain Seal Temperature (Cover Plate)	413	2,000
Maximum Drain Seal Temperature (Plug)	308	3,000
Maximum Cask Outer Surface Temperature	670	1,600
Maximum Impact Limiter Temperature	980	450
Cavity Pressure Rise, (kPa) g	135	3,000

* **Approximate Time from Start of Fire**